INVESTIGATION OF THERMAL REGIMES OF LAKES USED FOR WATER SUPPLY AND EXAMINATION OF DRINKING WATER SYSTEM IN KOTZEBUE, ALASKA

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ABSTRACT

Many villages in Arctic Alaska rely on lakes for water supply, such as the Alaskan City of Kotzebue, and these lakes may be sensitive to climate variability and change, particularly thermal regimes and corresponding effects on water quality. Thus, I initiated a study of water supply lakes in Kotzebue to collect data for developing a model to hindcast summer thermal regimes. Surface (T_{ws}) and bed (T_{wb}) temperature data collected from two water supply lakes and two control lakes from June 22nd – August 28th 2011 showed a similar pattern in relation to air temperature (T_a) and solar radiation with more frequent stratification in the deeper lakes. The average T_{ws} for all lakes during this period was 14.5°C, which was 3.4°C higher than T_a for the same period. I modeled T_{ws} from 1985 to 2010 using T_a and theoretical clear-sky solar radiation (TCSR) to analyze interannual variability, trends, and provide a baseline dataset. Similar to patterns in T_a for this period, I found no trend in mean T_{ws} for the main lake used for water supply (Devil's Lake), but considerable variation ranging from 12.2°C in 2000 to 19.2°C in 2004. My analysis suggests that 44% of years during this 25 year period maximum daily T_{ws} surpassed 20°C for at least one day. This hindcasted dataset can provide water supply managers in Kotzebue and other Arctic villages with a record of past conditions and a model for how lakes may respond to future climate change and variability that could impact water quality.

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CHAPTER 1: INTRODUCTION AND STUDY BACKGROUND

1.1 The importance of lakes in the Arctic

The Arctic coastal plain in northwestern Alaska is studded by hydrological features (Figure 1.1) with thousands of lakes dominating this picturesque landscape. These very important ecosystems store large amounts of water, affect regional hydrological patterns and climate, as well as adjacent ground including permafrost. These predominantly thermokarst lakes are important components of the water and biogeochemical cycling of Arctic Coastal Plain landscapes. Because lakes are abundant throughout large portions of the Arctic, they have an enormous regional influence on landscapes and ecosystems. They can moderate local climate by absorbing heat in hot weather and releasing heat during cooler conditions, and also help ease impacts of both floods by storing large amounts of water and droughts by providing water previously accumulated (Wetzel 2001). In addition, they provide habitat for many aquatic organisms, and are part of food web that also supports many terrestrial species (Warwick & Laybourn-Parry 2008). Therefore, lakes represent a key landscape component in the Arctic.

Figure 1.1 Hydrological features including lakes on the Arctic coastal plain.

Not only do fish, birds and other animals rely on the services that lakes offer, but people also are highly attached to and dependent on freshwater lakes. Near many towns and villages, Arctic lakes provide a valuable and stable supply of water for drinking, washing, and other municipal uses. Lakes are an important municipal water source, especially in many areas where fresh groundwater is not accessible. Fifty four Alaskan villages, over 4,000 people, rely on lakes or reservoirs as their drinking water source (State of Alaska 2011) and even a larger number of small villages rely on lakes for subsistence resources. Unfortunately, problems with source lakes have been recently observed in Arctic Alaska. In a study by Brubaker et al. (2009), increase in incidence of algal blooms in a water supply tundra lake for Point Hope was noticed causing economic and labor problems in water treatment procedure. The increase in severity of algal blooms and related diminishing drinking water quality is believed to be due to warming water induced by climate change observed in the area. Additionally, Brubaker et al. (2009) concluded that Point Hope is susceptible to hydrologic changes including water shortages influenced by alterations to annual precipitation and temperature. Because Kotzebue, the area of this study, uses two thermokarst lakes for their drinking water supply, and local air temperatures have raised at a similar rate as in Point Hope, there is a common concern.

1.2 Background to the Arctic lake thermal regimes

Water temperature is a significant factor largely defining lake ecosystems, as it has a great influence on hydrology by being one of the driving forces of the hydrologic cycling, on water quality, and productivity and sustainability of ecosystems (Kalff 2001). Thermal stratification, presence of ice-cover, concentration of dissolved oxygen, respiration and metabolism of fauna and flora, and also toxicity of pollutants are all substantially affected by a lake's water temperature (Kettle et al. 2004).

Lake water temperature is influenced by weather, lake morphology, water chemistry and surrounding topography (Sharma et al. 2008). Arctic lakes experience all means of heat transfer: convective, conductive, and radiative; and latent heat associated with phase changes. Heat transfer within a water-body is due to convection, the transfer of energy by bulk motion of fluids. Conductive heat transfer, the transfer of energy by vibrations at a molecular level, occurs, for example, when water accepts heat from warmer sediments ashore or when warmer lake water warms the underlying sediments. Radiative heat transfer, the transfer of energy through electromagnetic waves, is represented, for example, by solar radiation affecting the lake surface. Latent heat associated with phase changes is represented by processes of evaporation/ condensation, solidification/thawing, and sublimation/deposition (Hostetler 1995).

Because a lake's surface is the interface with atmosphere, the surface water temperature is directly affected by meteorological quantities. The most significant relationship of surface water temperature is to air temperature and solar radiation (Kettle et al. 2004).Other climatic variables are wind, latent heat flux, and cloud cover. Water temperature also depends on morphological attributes such as lake's surface area and mean depth, and on flux of surface and groundwater. Although there is a direct relationship between lake water temperature and air temperature, this relationship can vary due to differences in water color, turbidity and salinity (Edmundson & Mazumder 2002).

Lake thermal regimes are absolutely crucial for characterizing structures of biotic communities and productivity patterns of freshwater ecosystems (Kalff 2001) and, therefore, the lake thermal regimes and the stratification patterns, water temperature changes within water column, are very important and valuable to study. Distinct annual stratification patterns represent the criteria of lake classification. Lake stratification is typically described in terms of development of three layers in the water column characterized by temperature gradient with depth. This phenomenon is driven by a non-linear relationship between water density and temperature such that the maximum density occurs at about 4°C (Vedamuthu et al. 1994); water density is also affected by salinity. Therefore, lakes have the same temperature throughout their volume in two cases; water density is roughly uniform and lakes are mixed when 1) their temperature is about 4°C or, 2) wind currents or other mixing forces such as surface or groundwater flux are strong enough to cause turbulent mixing through the entire volume to keep lake's temperature uniform (Kalff 2001).

A lake becomes stratified when such increase or decrease in temperature occurs in the top layer that a difference in water density is developed to such extent that resistance against mixing is stronger than mixing. Therefore, stratification may occur with both, warmer temperatures than 4°C atop (summer stratification) or with colder temperatures than 4°C atop (winter stratification). Water generally mixes again with the opposite air temperature trend than the one which caused the stratification (cooling after summer stratification / warming after winter stratification). The change from stratified to mixed water column is called the turnover and the duration is called circulation period (Kalff 2001).

Lakes are often classified according to their stratification patterns. For Arctic regions, where lakes are characteristic for a brief ice-free summer season, following classes of lakes are relevant: 1) Amictic lakes are almost permanently covered with ice and their mixing is very limited; 2) Cold monomictic lakes are covered by ice for most of the year. They experience a brief ice-free period during summers, when their temperature does not exceed 4°C and wind caused turbulences keep lakes mixed; 3) Cold polymictic lakes experience several mixing events annually. These lakes are relatively shallow or located in windy regions, and are frozen except of during summer months. The shallower lakes (< ~ 20 m) finely stratify during warmer days and turnover at night. Deeper lakes stratify for up to several days or weeks. 4) Dimictic lakes are typical for regions with temperate climate and are characteristic by summer and winter stratifications and fall and spring mixing. 5) Discontinual polymictic lakes are a transitional group between the cold polymictic and dimictic categories (Kalff 2001).

Although Arctic lake temperatures have been studied by limnologists since the 1950s; there is still much to be discovered about their state and processes, such as lake thermal regimes. Due to the large area of the Arctic and its low human population, only relatively a few lakes have been examined for their thermal regimes. As early as in the 1950s, water temperature variations of as much as 4°C change in one day were described (Boyd 1959) and quite high surface temperatures of about 13°C were noticed in northern Alaska in summertime (Livingstone et al. 1958).

In recent years, rapid surface water warming has been described worldwide with stronger trends in high latitudes (Schneider & Hook 2010). Air temperatures in many parts of the Arctic show increasing trends (Overpeck et al. 1997; Kaufman et al. 2009) and the surface water temperature has been affected (Prowse et al. 2006). The climate of the Arctic has changed much more rapidly than it has globally and this trend is anticipated to continue (IPCC 2000). In many studies, the lake thermal regimes reflect such trends, for example, by overall increase in lake water temperature and altered timing of ice-cover and stratification (Lemke et al. 2007; Dibike et al. 2011). Arctic lakes are increasingly sensitive to climate change (Prowse et al. 2006; Smol & Douglas 2007). It is predicted by Hobbie et al. (1999) that when warming thaws the upper layers of permafrost, lakes become enriched by phosphorus. The slight eutrophication combined with increased stratification caused by warmer temperatures could decrease oxygen in the hypolimnion (Hobbie et al. 1999). In addition to the water-quality concern related to eutrophication and algal blooms, water quantity concerns are also in place in the Arctic especially due to the lake thermokarst character. Thermokarst lakes originated as small thermokarst features from a disturbance in permafrost which they are embedded in. They are characteristic by growing lake basins caused by thermal erosion and development of taliks, thawed permafrost underneath (Yoshikawa & Hinzman 2003). Abrupt Increase in permafrost degradation have been detected in Alaskan Arctic (Jorgenson et al. 2006). Enhanced rates of thermal erosion and talik development may lead to internal drainages and shrinking of pond surface areas (Yoshikawa & Hinzman 2003). Changes in Arctic lake surface areas related to climate change (Riordan et al. 2006; Smol & Douglas 2007; Jones et al. 2011) and to resulting altered water balance (Smith et al. 2005; Plug et al. 2008) have already been described (). Degrading permafrost has also been associated with changes in water quality in adjacent lakes (Kokelj et al. 2005).

A wide range of lake responses in discontinuous and continuous permafrost to environmental phenomena has been observed in the Arctic. In analysis conducted by Smith et al. (2005) regionally variable shifts in lake surface area changes were revealed. Increases in surface areas and new emerging lakes were observed in regions with continuous permafrost and decreases in surface areas and disappearance of lakes were observed in regions with discontinuous permafrost. The boundary between the two regions seemed to be shifting northward (Smith et al. 2005). Generally, predicting lake thermal regimes is quite difficult because of the amount and variety of predictor variables coupled with the high heat capacity of water, latent heat associated with phase change, and a strong seasonality of ice cover (Dibike et al. 2011).

1.3 Rationale of the project

This project reveals information on summertime thermal regimes of four studied water-bodies located in north-western Alaska near Kotzebue. Such information is useful purely on its own as a new experiment giving knowledge about daily and yearly thermal variations of selected Arctic lakes. Above all, here, this knowledge is particularly useful because the lakes are vital to the Kotzebue community of over 3,200 people. The need to understand vulnerabilities of village water supplies have been studied in Alaska by for example Marino et al. (2009) and White et al. (2007). However, any studies that would integrate investigations of lake thermal regimes related to climate change and their function as community drinking water source have not been discovered.

I have chosen to study lakes in north-western Alaska near Kotzebue for three reasons. First, there is a need of baseline temperature datasets for lakes in the Arctic. In these regions, climate has been changing more rapidly than in other latitudes (Overpeck et al. 1997), and lakes are particularly sensitive to it (Riordan et al. 2006; Dibike et al. 2011). The four studied water-bodies are also a part of a larger project "Thermal response of western Alaska lakes and lagoons to past, present, and future changes in climate" (Alaska WLCC, principal investigator: B. M. Jones), which aims to monitor over 50 water-bodies in western Alaska. Second, Kotzebue has a long term weather station at the Ralph Wien Memorial Airport which has monitored meteorological variables since the 1950s. Third, I have chosen lakes near Kotzebue because they serve as a municipal water source for the City. I was curious, how drinking water systems and treatment plants operate in the Arctic, considering the challenging climatic conditions and remoteness. This part of our investigations was included in the project "Municipal Water Systems & Resilience of Arctic Communities" (principal investigator: L. Allesa). I have examined the water treatment plant (WTP) and municipal water system in Kotzebue and particularly focused on the source lakes as they are the key components of the system with regard to resilience of the community. I combined goals of both projects and decided that the water source lakes near Kotzebue make a perfect subject of my study. In sum, although the City of Kotzebue has a relatively large population and extensive water supply system compared to many villages in western Alaska, its use of lakes for water supply and proximity to long-term climate station made it a logical place to conduct my research. Our current lack of understanding about how lakes will respond to climate change, particularly with respect to village water supply systems, has been recognized by the Alaska Native Tribal Health Consortium (ANTHC), as well as the U.S. Geological Survey (USGS), National Science Foundation (NSF), and U.S. Fish and Wildlife Service's Western Alaska Landscape Conservation Cooperative (AK WLCC).

I hypothesized that the summer surface water temperatures in lakes near Kotzebue were generally higher than air temperatures. Studies by Kettle et al. (2004) and Arp et al. (2010) came to such conclusion, but a study by Livingstone et al. (1958) showed just opposite. I also hypothesized that the water supply lakes respond to changing air temperatures and solar radiation in a similar manner as the un-managed thermokarst lake. This research is a coupled monitoring and modeling project, so the objective was to use the relationship of monitored surface water temperatures to air temperature and solar radiation and use it for hindcasting of past thermal regimes. I had an opportunity to monitor the lakes over the summer of 2011, specifically from June 22nd until August 28th. I have chosen to model and hindcast data from time-period starting July 1st and ending August 15th, because using this modeling approach, modeling of the entire monitoring period would be inaccurate.. I have selected Devil's and Vortac Lakes for our study, because they are extremely important for the City of Kotzebue as they serve as a source of drinking water for the community. If their thermal regimes significantly changed, it could affect the drinking water quality and availability. An arising question was whether the man-managed water supply lakes significantly differ in their thermal regimes from a tundra lake with natural water-balance. Therefore, besides the two source lakes, I have also chosen to monitor Mosquito Lake and Kotzebue Lagoon (later just Lagoon) for reference. In order for us to better understand the local drinking water supply situation, especially with regard to the challenging Arctic conditions and the remote area; I evaluated the drinking water system and treatment plant and its operations.

Therefore, the main purpose of this study was to establish a baseline of interannual variability, a modeled record, a point of reference of water temperature data, for lakes near Kotzebue including two water supply lakes. Because the biological, physical and chemical characteristics are closely related to a lake's thermal regime, information from this study on lake water temperature responses to seasonal weather patterns and interannual climate variability should assist the water treatment plant management and the City with planning and future vulnerability/resilience assessment. In Kotzebue, I met people highly committed to providing healthy drinking water to the City, deeply caring about their service to the community; and that motivated me even more in my efforts to provide them with scientific information on lake thermal regimes.

The hypotheses tested in this thesis are: 1) The summer surface water temperatures in lakes near Kotzebue were generally higher than air temperatures. 2) The water supply lakes respond to changing air temperatures and solar radiation in a similar manner as the un-managed thermokarst lake.

1.4 Kotzebue and its drinking water system

Kotzebue

Kotzebue is located in north-west Alaska (66°54‘N 162°35‘W) just 45 km north of the Arctic Circle (Figure 1.2). Its climate is characterized by long, cold winters and short cool summers. In the 1971-2000 time period the average annual temperature was -5.7°C, average winter temperature was -18.9°C and average summer temperature was 10.3°C. Annually, Kotzebue receives 250 mm of precipitation including over 1,000 mm of snowfall (100 mm of snow water equivalent). Increasing trends of mean annual temperature and total annual precipitation have been recorded in Kotzebue over the time period of 1950-2005 (Arctic Climate Research Center 2012). The city’s position on the Baldwin Peninsula gives it characteristic maritime climate influence. The city was built on a spit of land just about 5 km long and between 300 m and 1 km wide. This geographical feature is to be found on the north-west end of Baldwin Peninsula and surrounded by Kotzebue Sound, a part of the Chukchi Sea which is ice-free from early July until early October. Major rivers: Noatak, Kobuk, and Selawik, drain into Kotzebue Sound and thus provide natural transportation pathways. Therefore, Kotzebue is the transfer point between ocean and inland shipping. Besides water, air is the primary means of transportation year-round. Daily flights to Anchorage and to the region’s villages leave from the local Ralph Wien Memorial Airport. Locally, cars, trucks, four-wheelers, snow-machines and boats are used for transportation (State of Alaska 2011).

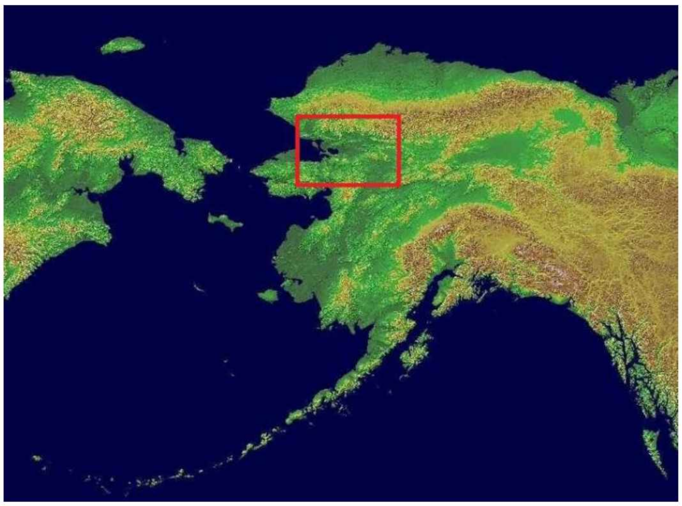

Figure 1.2 Kotzebue and our study sites are located on the Baldwin Peninsula near the coast of north-western Alaska.

The area has a very long tradition as it has been inhabited by the Inupiat Eskimos for at least 600 years and represented a busy crossroad of ancient trading routes. The Europeans established contact with the community in 1800s and the city was formed in mid-20th century. Presently, Kotzebue has a population of over 3,200, mainly Inupiat Eskimos, and serves as a regional hub of the Northwest Arctic Borough. It offers numerous services, including health care provided by the Maniilaq Hospital, to the people from villages in the northwest region. Many public agencies such as the U.S. National Park Service, Bureau of Land Management, and the U.S. Fish and Wildlife Service are stationed in the city as well. The city has its own drinking water treatment plant (WTP), sewage system, electric plant and a landfill. Waste water is treated in a lagoon located in between the Kotzebue Lagoon and the Kotzebue Sound (State of Alaska 2011).

Municipal Water Treatment Plant and Drinking Water System

The Kotzebue Water Treatment Plant (WTP) is located in the City of Kotzebue on the Third Avenue (Figure 1.3) and was first developed in 1966. In 1999, major reconstruction took place to upgrade the water distribution system. Now this Level 3 plant is operated by four skilled people. Randy Walker is the supervisor and Matthew Lazarus is an operator who has helped familiarize our group with the system. The Kotzebue Water Treatment Plant is highly manually managed and not completely automated. It runs continuously with a passage of about 950 L (250 gallons) per minute, and treats water for a wide range of pollutants. The water treatment operations are very cost and labor intensive and the plant takes quite a lot of space compared to some other WTP in Alaska. The water cost in 2011 was $ 69/month flat rate per household and $ 30 per 3.8 m^3 (1000 gallons) for metered commercial users and those who need water delivered (there is a $ 45 truck delivery charge). The electric rate of the plant was about $ 10,000 per month. In case of a power shortage, there are diesel generators in the WTP and in both pump houses.

Figure 1.3 The city of Kotzebue is located on a narrow spit of land. The WTP including two light-blue water storage tanks is on the right-hand side of the picture.

Our research group visited the plant on June 20th 2011. Randy Walker and Matthew Lazarus were very helpful showing us the plant and providing a lot of interesting information about the system, and explaining to us the processes which are used to treat the water and their responsibilities as plant operators. I was very impressed by their work and commitment to supply the town with healthy, tasty drinking water.

In Kotzebue, two thermokarst lakes serve as sources of drinking water for the town; Devil's Lake and Vortac Lake are located on Baldwin Peninsula just east of the city. Devil's Lake is about 5 km from the city; Vortac is a little closer, about 3.5 km. Both lakes are uphill from the city (Figure 2.6). Vortac Lake, originally a natural reservoir, has a man-made dam. The dam is deteriorating; therefore, in the summer of 2011, intense drawing of water out of Vortac Lake was taking a place as to relieve some pressure off the dam. Water from Vortac Lake was pumped in two directions: directly to the water treatment plant and then the drinking water system; and to Devil's Lake which is larger and can hold greater volume of water.

During winters, water is pumped only from Devil's Lake (Figure 1.4) where air bubbling by the water intake inhibits freezing of a portion of lake's surface. Ice on the rest of the lake can be over 1 m thick. Devil's Lake is in close-to-shore portions about 1 m deep and its depth increases to about 3 m. A few random spots were artificially dredged to increase the lake's volume creating depths of about 6 m. However, lake depth seasonally varies with the lowest level right before spring melt. Water quality also changes throughout the year; for example in April, it has degraded quality due to long stagnation of water underneath the ice and high concentrations of salts. The WTP operators mentioned that the water quality is about the same in both lakes with slightly higher alkalinity of Vortac Lake. Alkalinity is usually higher during

Figure 1.4 Pump-house at Devil's Lake and old rotting mains on its shore.

winters. There is no fence or any barrier around either lake as to prevent possible contamination. The area around the lakes is heavily used both in winter and summer months. There is a snow-machine trail in winter across Devil's Lake and a network of four-wheeler trails around the lakes.

Water pumped from Vortac and Devil's Lakes is delivered by a pipeline to the WTP which is located in the town. It takes about 8 hours for water to travel from the lakes to the WTP. About ¾ of this pipeline are buried and ¼ remains on surface. The burying of the pipeline took a place quite recently along with the replacement of the section that runs from Vortac Lake to the plant. Because there are more stable thermal conditions underground than on the surface, the burial of pipelines has proven to be advantageous. An increase has been observed in raw water temperature coming to the plant by about 1.1°C (2°F) in winter, from 0.3°C (32.5°F) to 1.4°C (34.5°F). The pipeline is well insulated and heat traced to prevent water from freezing (Figure 1.5).

Figure 1.5 Cross-section of a pipe for raw water delivery which reveals a thick insulation layer and heat tracing.

The pipeline brings more than 1,135 m^3 (300,000 gallons) of water to the WTP daily of which 95% is distributed to users and the remaining 5% is either used for backwashing or is lost. Because water needs to be supplied year round, there is a constant drawing of water from the lakes. As I learned from the WTP operators, it is important to keep the system going and to constantly pump water, otherwise a problem of system's freezing could occur during the days when temperatures are below freezing point.

In order to understand the municipal water system and its flexibility/dependency on the source lakes, I examined the water treatment procedure. When the raw water is being treated, it first passes through the Johnson's screen which surrounds each of the submersible pumps in the lakes. Big objects are removed and so pipes are prevented from clogging. Raw water enters the plant under varying pressures depending on how much is needed at a given time.

In the Kotzebue WTP, the first chemical added into the raw water is potassium permanganate, $KMnO_4$. This treatment chemical can act as a disinfectant, but serves primarily as an oxidizing agent to remove iron, manganese, hydrogen sulfide and other natural organics as well as some tastes and odors. The water is also aerated to release the unwanted gases. Alum, aluminum sulfate, $Al_2(SO_4)_3{\cdot}18\ H_2O$, is added into the raw water next which moves into the detention tank. Alum serves as coagulant which binds together very fine suspended particles into larger particles. Because alum forms aluminum hydroxide precipitate, it pulls hydroxide ions out of the water which lowers its pH. Two organic polymers are added into the raw water which then moves into a mixing tank. Mixing is particularly important and the polymers, clear viscous liquids, allow fine suspended particles to bind into larger particles that can be removed by settling and filtration. The advantage of the polymers is that they do not affect pH and work at much lower doses than for example solely alum.

Figure 1.6 One of the two treatment units which of multimedia filter is being manually washed.

Water moves to one of the two treatment units (Figure 1.6). Each unit consists of four chambers within one large, rectangular open top tank. The first one serves for coagulation, second for flocculation, third is called a clarifier and the fourth one is the granular filter. It takes roughly 2 hours for water to pass through the treatment unit including the multi-media filter at the end. The multimedia-filter is about 1.8 m (6 feet) tall and consisted of multiple layers with the coarse but lighter particles atop and finer but heavier particles at the bottom of the bed. Also, water is well mixed prior to entering the filter and activated carbon is added just before the water enters the first chamber of the unit. The activated carbon was initially used after people's complaints in summer 2005 about an unpleasant taste and odor of water. This was caused by a strong algal bloom. Since then, people became used to not tasting the organics or smelling algal odor in their water, therefore, the filtering method with use of activated carbon has been used constantly ever since. The amount of the powdered activated carbon corresponds to the severity of algal bloom. After water passes through the multi-media filter, 1) chlorine for disinfection, 2) soda ash for pH adjustment (pH 7.5), and 3) fluoride for prevention of tooth decay are added.

Before the treated water enters the distribution system; it has to pass through one of the two storage tanks (Figure 1.7) with a volume of 5,700 m^3 (1.5 million gallons) each. The tanks are constantly connected to the system as water goes through them to the loops. This is very advantageous as water stays on average in a tank only for about 10 days. It doesn't stay there too long to stagnate, which could possibly deteriorate water quality. Additionally, the tanks are always full and ready in case of a raw water supply shortage or a problem in the WTP. Also, the distribution system is well regulated through the water tanks. In the City of Kotzebue, there are also fire pumps and extra water tanks by bigger buildings such as hospital or school to store water in case of a problem.

Figure 1.7 Storage tanks with treated water.

There are six loops of the city distribution pipelines in which water is circulating continuously. The six loops distribute about 1,100 m^3 (300 000 gallons) of drinking water daily. Kotzebue has about 3,200 people and that corresponds to about 350 L (94 gallons) of water per person per day. Water in one of the six loops heats up at the power plant and from that one loop the entire system of all six town loops warms up. In winter, water entering the system can have a temperature as low as about 2.2°C (36°F). Heated water is about 15°C (60°F) which brings all water in the loops to about 7°C (45°F).

Permafrost makes it more challenging for the underground distribution system as the frozen ground may thaw and become unstable, or may even heave and cause serious damage to the system. A little crack could cause water leakage and also contamination of the drinking water during times of low pressure in the distribution pipeline. Water mains enter people's homes through the "Arctic Box" which is heat traced as to prevent pipes above ground from freezing.

Figure 1.8 Small laboratory at the Kotzebue WTP.

Some water quality measurements are conducted directly in a laboratory in the plant (Figure 1.8). The measurements used in both raw and treated water are temperature, pH, color, turbidity, alkalinity, hardness, and odor. Chlorine, fluoride and taste are also examined in treated water. Amounts of raw water, treated water (combined filter effluent) and water supply in each loop are also recorded. The plant reports its data monthly to Alaska Department of Environmental Conservation. Also some additional testing, such as total organic carbon and coliform bacteria (monthly), volatile organic compounds (quarterly), nitrates, nitrites, arsenic and other inorganic chemicals (once a year) or radionuclides (once in a couple of years), is conducted by Analytica based in Anchorage. The water is no longer tested for herbicides, pesticides or other synthetic organic contaminants due to negative results of previous testing and the improbability of their occurrence.

Regarding the current and possible future problems and vulnerabilities of the system, according to the plant operators, sometimes they had a trouble getting rid of disinfection byproducts, chlorinated organics. It is also more difficult to treat water in winter when water contains higher levels of Fe and Mn and alkalinity is high due to ice-formation and resulting increase in concentration of the ions in remaining liquid water. Therefore, higher alum additions are required in winters. In summers, algal blooms represent a problem as they create unpleasant odor. Powdered activated carbon proved to work well to cope with that problem. According to the plant operator, the issues in the water treatment plant are mostly not Alaska climate or location specific (Matthew Lazarus 2011, personal communication). However, the Alaska specific problem is the distribution system’s vulnerability due to the frozen ground that the pipes are in.

CHAPTER 2: METHODS

2.1 Description of study area

Increasing trends of mean annual temperature and total annual precipitation have been recorded in Kotzebue over the time period of 1950-2005 (Arctic Climate Research Center 2012). However, these trends have been affected by the Pacific Decadal Oscillation which caused a climatic regime shift in the late 1970's (Mantua et al. 1997). I calculated with data monitored at the Kotzebue airport, that in the 1985-2011 time period the average annual temperature was -5.13°C, average winter (December, January, February) temperature was -18.1°C and average summer (June, July, August) temperature was 10.5°C. Temperature extremes of - 45°C and +29.5°C were both recorded in 1991.

Analysis of mean annual air temperatures recorded in Kotzebue for the time period of 1985 – 2011 showed a weak increasing trend of 0.04°C per year (R^2 =0.08; p-value= 0.15) (Figure 2.1). The annual air temperature means varied among years and ranged from -7.7°C to -3.1°C. The coldest years were 1999 and 1992 with mean temperatures below -7°C and the warmest years were 2004, 2002, 1998 and 2003 with mean temperatures above -4°C. .

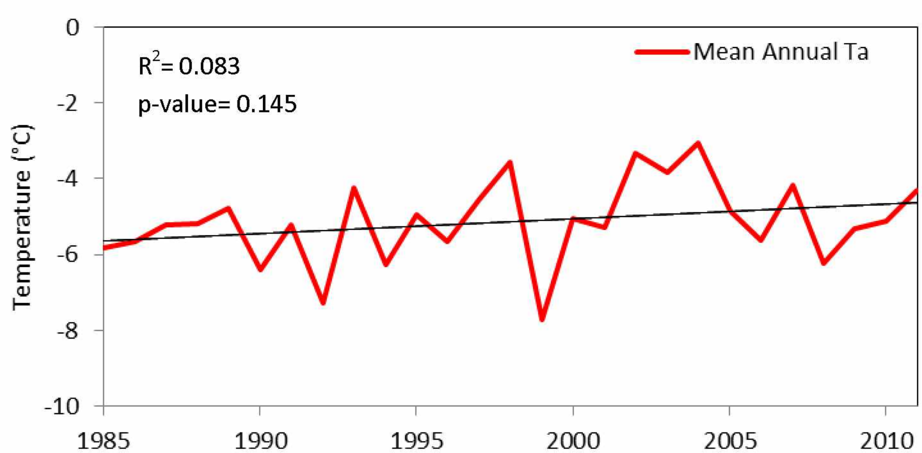

Figure 2.1 Mean annual air temperatures monitored in Kotzebue during the time period of 1985-2011.

Analysis of mean summer (June, July, August) temperatures, however, showed no trend during this same period, but revealed considerable interannual variability ranging from 8.4°C to 14.1°C (Figure 2.2). The coldest summers were in 2000 and 2006 with mean summer temperatures below 9°C. The warmest summer occurred in 2004 (mean T_a = 14.1°C); second and third warmest summers were recorded in 2007 and 1990 with temperature means above 12°C. It is quite interesting that only the warmest summer and warmest year correspond (2004) and other records of warmest/coldest summers do not correspond with warmest/coldest years.

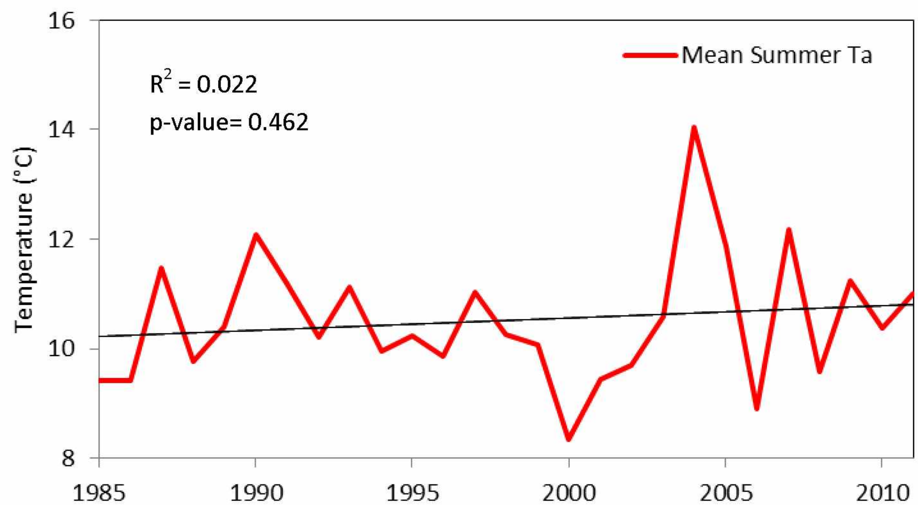

Figure 2.2 Mean summer (June, July, August) air temperatures monitored in Kotzebue during the time period of 1985-2011.

The mean air temperatures for the time period used for modeling and hindcasting, July 1st – August 15th, do not show any increasing trend between 1985 and 2011 (Figure 2.3). The

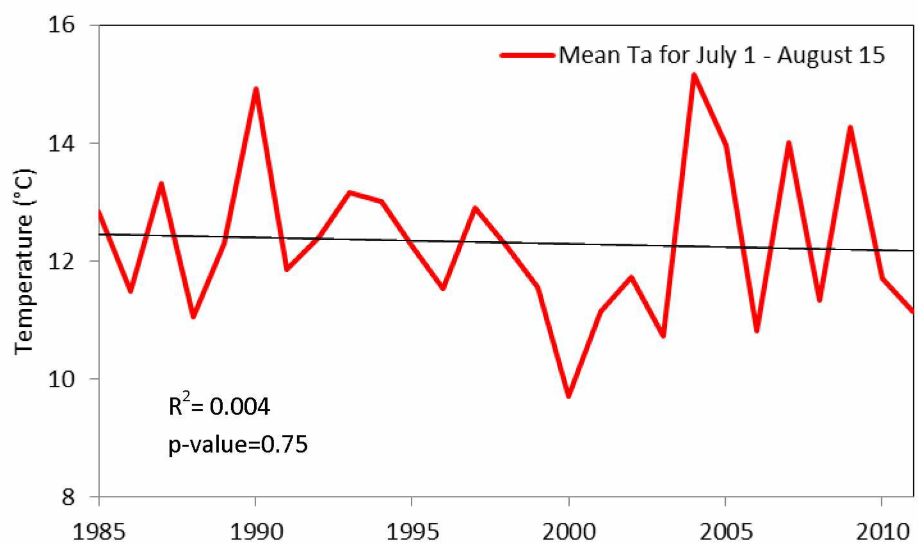

Figure 2.3 Mean air temperatures for the modeling and hindcasting time period, July 1st – August 15th, for the time-frame of 1985-2011.

air temperature means for July 1st – August 15th vary among years and range between 9.7°C and 15.2°C. The years with coldest mean air temperatures for July 1st-August 15th were in 2000, 2003 and 2006 with mean temperatures below 11°C. The years with warmest mean air temperatures for July 1st-August 15th were 2004, 1990, 2009 and 2007 with temperature means above 14°C. These years correspond well with years with coldest/warmest summers.

In Kotzebue, the mean of annual precipitation for the years 1985-2011 was 283 mm. The total annual precipitation ranged between 192 mm (2007) and 421 mm (2009) (Figure 2.4). The three years with the highest total precipitation were 2009, 1990 and 1998. The three years with the lowest total precipitation were 2007, 1987 and 1999.

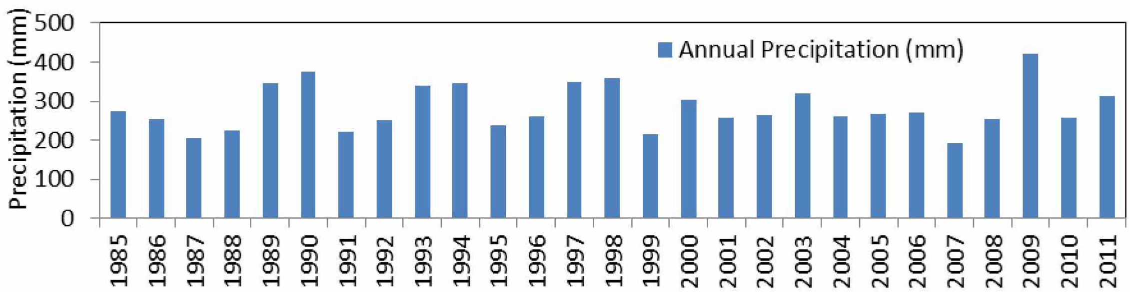

Figure 2.4 Annual Precipitation in Kotzebue in years 1985-2011.

The mean of total summer (June, July, August) precipitation in Kotzebue was 105 mm for the years 1985-2011. The total summer precipitation ranged between 56 mm (1991) and 208 mm (1998) (Figure 2.5). The three summers with the highest total precipitation were in 1998, 1994 and 1989. The three years with the lowest total precipitation were 1991, 2002 and 2007.

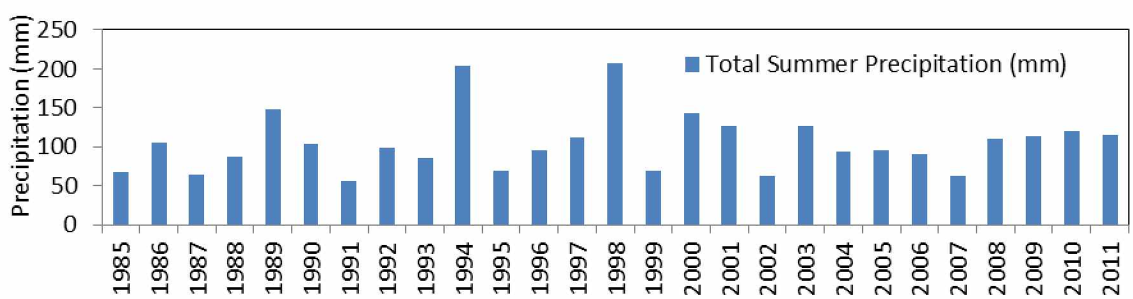

Figure 2.5 Total precipitation in summer months (June, July, August) in Kotzebue for the time-frame of 1985-2011.

Prevailing winds are east-northeast and east-southeast. Because of the area's position north of the Arctic Circle, Kotzebue experiences 24 hours of daylight in the summer solstice and 24 hours of darkness in the winter solstice. Although Kotzebue receives a lot of daylight during summer, growing season is quite short. Tussock tundra present in the area is the vegetation composed of grasses, for example white tussocks cottongrass (*Eriophorum vaginatum*), sedges (*Carex bigelowii, Carex lugens*), dwarf shrubs, for example willow shrubs (*Salix arctica, Salix ovalifolia*), dwarf birches (*Betula nana*) and blueberry shrubs (*Vaccinium alaskaense*), mosses, and lichens (USDA 2012). The landscape in Kotzebue's vicinity is not completely flat; it is rather a slightly rolling countryside. Tundra in the area is very wet and waterlogged in places, as the presence of permafrost keeps water on the surface. Many features characteristic for thermokarst landscapes are in the area. I have noticed some typical patterns such as some dried lake basins as well as a deep empty basin which probably suddenly drained, and shoreline erosion characteristic for expanding thermokarst lakes.

Therefore, the four studied water-bodies are not the only hydrological features near Kotzebue and their "life" might be quite dynamic. They all are in proximity of the City of Kotzebue. Two of the four water-bodies, Devil's Lake ("D" in Figure 2.6) and Vortac Lake ("V" in

Figure 2.6 Satellite image of the study area showing positions of Devil's Lake (D), Vortac Lake (V), Mosquito Lake (M), and Lagoon (L) in vicinity of the City of Kotzebue. The green and pink dots mark locations of the airport weather station and our small weather station

Figure 2.6) are drinking water source lakes for the City. Devil's Lake is about 5 km south-east from the City and Vortac is closer; about 3 km. Kotzebue Lagoon ("L" in Figure 2.6) is the largest water-body and the closest to the town. It is connected to the Kotzebue Sound, therefore, its water is relatively saline and water level changes rapidly due to tidal forces. I chose Lagoon as a reference water-body in our study for two reasons: 1) It is large enough as to have its surface water temperature measured by the satellite MODIS; 2) It is the closest to the Ralph Wien Memorial Airport weather station (marked with a green sign in Figure 2.6) where the long-term climatological data for our study originate from. Mosquito Lake ("M" in Figure 2.6) is the most distant from Kotzebue. I chose this lake for reference because it is the closest similarly sized lake to the drinking water source lakes. Mosquito Lake is not man-managed, so it is particularly useful in answering the question if thermal regimes differ between lakes with man-altered water-balance and those with natural water-balance.

In the picture on the right, there is an aerial view on Devil's Lake with a pump house and pipeline (Figure 2.7). In the far left back, there is Mosquito Lake. Behind is water surrounding the Baldwin Peninsula. Devil's and Mosquito Lakes are quite similar in size and their surface area is 1.01 km^2 and 1.48 km^2 respectively. The surface areas are believed to grow because they both are thermokarst lakes and they expand their basins by thermal shoreline erosion. Devil's Lake is deeper than Mosquito Lake with depths greater than 3.5 m compared to Mosquito's 1.5 m. Vortac Lake is smaller (surface area 0.41 km^2) than Devil's and Mosquito Lakes, and it is intermediately deep (2.3 m) relatively to the two other lakes. Elevation related to the sea level is very similar for all three lakes with Devil's Lake's 23 m above sea level and Vortac and Mosquito Lakes' 29 m. Lagoon is the largest water-body with surface area 3.88 km^2 and mean depth about 2 m. It is connected to the Kotzebue Sound and its elevation is about 5 m above sea level (Table 2.1).

Figure 2.7 Aerial view on the water intake at Devil's Lake. Mosquito Lake is located in the left back of this picture.

Table 2.1 Basic descriptive parameters of the four studied water-bodies: area, depth, elevation, location, dissolved organic carbon (DOC) and specific conductance.

Water-body	Area km²	Mean Depth m	Elevation m	Location	DOC, mg/L June/Aug	Specific Conductance µS/cm, June/Aug	Secchi depth, m
Devil's Lake	1.01	3.64	23	66°52' N 162°30' W	11.2 / 14.9	75 / 82	1.30
Vortac Lake	0.41	2.28	29	66°53' N 162°32' W	14.4 / 15.6	137 / 164	1.45
Mosquito Lake	1.48	1.56	29	66°53' N 162°27' W	12.3 / 13.0	100 / 108	1.05
Lagoon	3.88	1.99	2	66°53' N 162°35' W	11.0 / 15.6	5800 / 7800	0.50

In order to characterize lakes hydrologically, I focused on water level changes related to precipitation and management. Because water is being drawn from Vortac and Devil's Lakes for municipal uses, I was curious how rapidly water levels decrease, and how precipitation affects water level changes. Detailed study of water balance and water budget in each lake's watershed was not a subject of our project. However, such study would be useful as to provide information on sustainability of the source lakes supplying drinking water for the City of Kotzebue in current and future rates.

In order to view water level changes (Figure 2.8), changes in pressure were monitored on the bottom of the lakes and converted to changes in their depth (Onset HOBO U20 Data Logger and software). Substantial changes were observed and attributed to various phenomena: Devil's and Vortac Lakes' levels mainly reacted to their management,

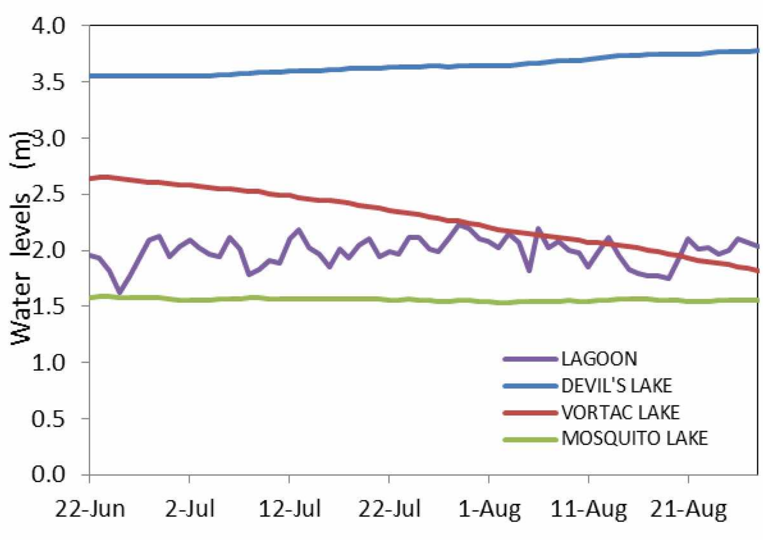

Figure 2.8 Water level changes in studied water-bodies, summer 2011.

Mosquito Lake's water level mainly responded to precipitation, and Lagoon's water level highly depends on tidal forces.

Changes in water levels are even more visible in following graph (Figure 2.9) which shows water level deviations from each water body's average of measured water depth over the studied period of time.

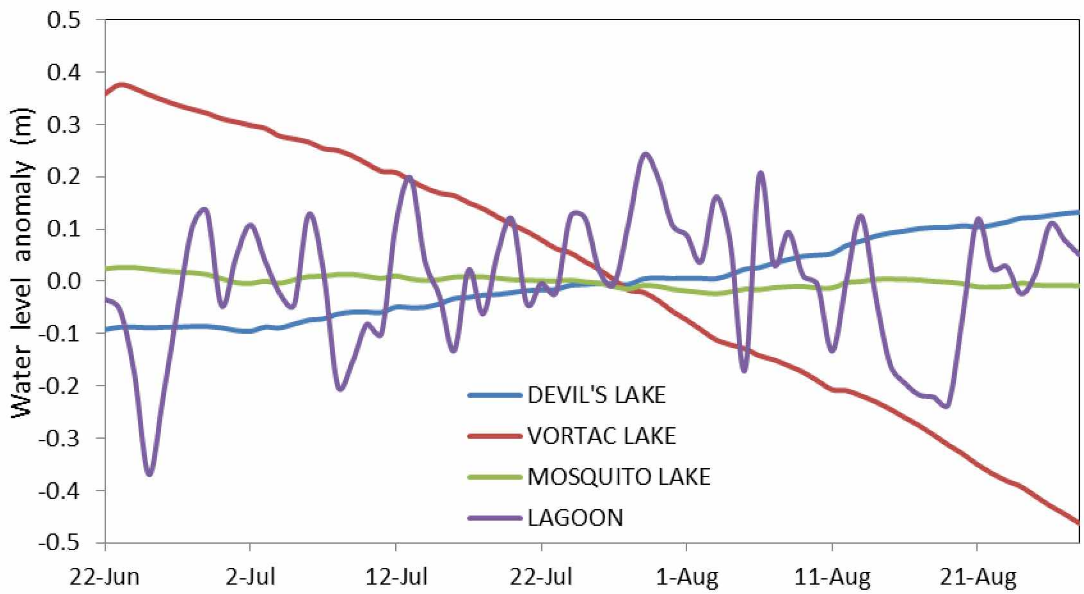

Figure 2.9 Water level anomaly - deviations from the average measured water level in each water body, summer 2011.

From our understanding, Lagoon was reacting to tidal changes because it is connected to the Kotzebue Sound. Devil's and Vortac Lakes are managed and used as a drinking water source for Kotzebue. Even more obvious rapid increase in water level of Devil's Lake and a rapid decrease in water level of Vortac Lake were later explained to us by the water treatment plant operators who managed the two source lakes in the summer 2011 in a manner as to protect a deteriorating dam on the Vortac Lake. Water was pumped from Vortac Lake to both, the drinking water system and the Devil's Lake for storage. Mosquito Lake, the control lake in our study, changed its level the least. It reacted to precipitation events (Figure 2.10).

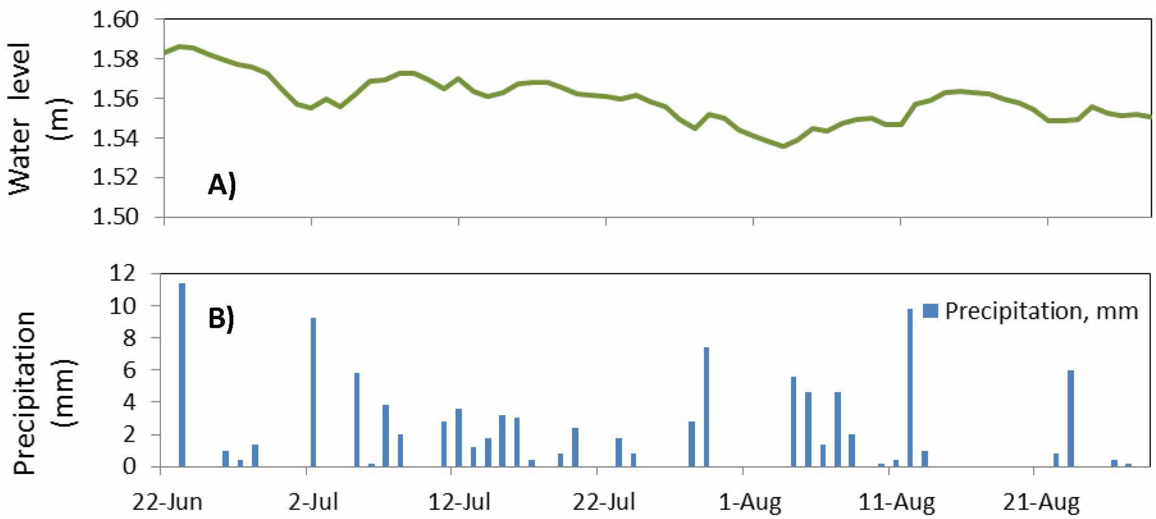

Figure 2.10 Changes in Mosquito Lake's water level (A) in reaction to precipitation events (B) monitored over the time period of June 22nd – August 29th, 2011.

2.2 Experimental design

Generally, to accomplish our project goals I began investigating two lakes being used for water supply by the City of Kotzebue and two adjacent reference water-bodies on the Baldwin Peninsula during the summer of 2011. At each lake, I monitored surface and bed water temperatures, water levels, and water pressure, along with weather parameters that overlap with meteorological data collected long-term (since 1950s) at the Ralph Wien Memorial Airport in Kotzebue. Data collected during this period were used to develop mathematical models for each water-body to simulate lake temperature regimes using an empirical approach based on air temperature and solar radiation. The monitoring approach to this project follows methods outlined and published in Arp et al. (2010) and the empirical modeling approach was demonstrated for lakes in Greenland (Kettle et al. 2004) and applied successfully to lakes in Alaska using remote sensing integration (Arp et al. 2010).

I used these models to hindcast summer lake thermal regimes from 1985-2010. Future validation of hindcasted values will be possible with use of the MODIS satellite surface water temperature measurements of Kotzebue Lagoon (monitored with sensors in summer 2011). Simulation of this time period will provide a reasonable baseline of thermal regimes of the water supply and reference water-bodies and their interannual variability. This dataset will also provide an opportunity to analyze if and how Arctic coastal lakes have changed during the past quarter of century.

2.3 Monitoring

Our first field work near Kotzebue in June 2011 included sensor and meteorological station installation, water sampling, bathymetrical measuring, land surveying and municipal drinking water system examination. Data collection from installed sensors was conducted during our second visit of the study site in August 2011. I focused only on the summer period because the model is intended only for open-water conditions with surface temperatures > 4°C and also because this is when water temperatures could impact water quality in terms of algal blooms.

In the spring 2011, prior to our field work, I prepared our equipment. I used autonomous sensors with internal dataloggers to monitor water temperature (HOBO Pro v2 Water Temperature Data Logger U22-001) and water pressure/water level change (HOBO U20 Water Level Data Logger). First, I calibrated these sensors in a liquid glycol calibration bath in a lab. I determined correction coefficients (intercept and slope) for each of them after monitoring temperatures of the glycol bath set on 20, 15, 10, 5 and 0°C. I decided for this range because I assumed that it is likely that the water temperatures would not exceed 20°C and certainly would not drop below 0°C during our studied period. After the calibration procedure, the sensors were launched for hourly data-logging intervals and attached to buoys to mark their location and a weight on the opposite end of a line to anchor them. The length of the wire was adjusted for each water-body's depth in a manner as to monitor water temperature near surface (10 cm below) and at the bed. The lake surface temperature (T_{ws}) data was collected to develop a modeling for hindcasting past T_{WS}. In the field, I used a small Alpaca raft for sensor deployment and water sampling off-shore, and took GPS coordinates of the monitoring locations.

A meteorological station was installed on the shore of Devil's Lake that measures air temperature, solar radiation, pressure, and precipitation. The studied relationship is between water temperature and air temperature and solar radiation, therefore, I used data monitored by this station to assess this relationship. Then I looked how well these values compared to the values monitored at Ralph Wien Memorial Airport weather station in Kotzebue, where climatological data have been regularly monitored long-term and served as input data for empirical model development as well as hindcasting.

2.4 Analyzing data

Data collected during summer 2011 were analyzed with use of Excel. Hourly water temperature values corrected by coefficients from a developed calibration sheet were averaged to obtain mean daily values. Graphs were prepared to show course of mean daily values since mid-June 2011 till late August 2011. I also compared meteorological quantities measured at our Devil's Lake weather station with values monitored at the Kotzebue airport. The airport weather data were obtained from the National Climatic Data Center: NNDC Climate Data Online at http://cdo.ncdc.noaa.gov/. I requested hourly intervals and converted those to daily averages.

2.5 Data modeling and hindcasting

The main project goal was to develop an empirical model relating change of water temperature to air temperature and solar radiation for each water-body, which was then used to hindcast summer lake surface temperature from 1985 to 2010. The model was driven using long-term air temperature data obtained from the Ralph Wien Memorial Airport weather station in Kotzebue (PAOT, WBAN: 26616, USAF: 701330; 66°53'N 162°36'W).

I followed methods used for development of a regression model as described by Kettle et al. (2004) which is also used by Arp et al. (2010). I decided for this particular approach because this model uses only air temperature and solar radiation as variables and, therefore, it is used for estimates of past surface water temperatures where comprehensive datasets including other variables affecting surface water temperature are not available. Air temperature and solar radiation are both important determining factors of lake heat balances. Additionally, air temperature is to a certain degree correlated with other variables used in more extensive models, such as relative humidity and cloud cover, therefore, it can partially compensate for their climatic signal. Surface water temperatures are applied into the calculations of multiple linear regressions, and relationship equations with specific coefficients for each water-body are estimated. Other lake water temperature models, such as MyLake (Saloranta & Andersen 2007), require more detailed time series of meteorological input data such as humidity and wind speed, and other variables such as mean lake depth and thermal interaction between the water column and the bottom sediment.

Air temperature was measured at the Devil's Lake shore over the monitored period of time between June 22nd and August 29th. Because the four studied water-bodies are very close one to another, I assumed that air temperature is the same for all of them. Then I compared the values from Devil's Lake weather station to values detected at the airport to be sure they are similar enough that I could use the airport data for model development and hindcasting. (The airport weather station is actually closer to Lagoon than our weather station is, but further away from other three water-bodies.)

Solar radiation, the second variable for our model, was measured and also estimated for the time period and area in my study. Because solar radiation has not been recorded at the airport weather station, I used the Theoretical Clear Sky Solar Radiation Model developed by Richard E. Bird (Senior Scientist at Solar Energy Research Institute, Golden, CO) and described in Bird & Hulstrom (1981). This theoretical method estimates clear sky solar radiation on the ground surface based on calculation of the solar position and atmospheric attenuation (Annear & Wells 2007). The model is based on comparisons with results from rigorous radiative transfer codes and the results should be expected to agree within ± 10%. The model is a broadband algorithm which produces estimates of clear sky direct beam, hemispherical diffuse, and total hemispherical solar radiation on a horizontal surface. The model produces estimates of solar radiation for every hour of the year, based on the 10 user input parameters. I used a user friendly pre-programmed Excel spreadsheet created by Daryl Myers (National Renewable Energy Laboratory), and pasted location specific data into defined input cells. These were for our study area: Latitude: +67, Longitude: -162, Time Zone: -9, Pressure mB: 1004 (1004 mB was the average in summer 2011), Ozone cm: 0.3 (default), H_2O cm: 1.5 (default), AOD (Aerosol Optical Depth) @ 500 nm: 0.1 (default), AOD@ 380 nm: 0.15 (default), Taua (Aerosol Optical Depth in UV): 0.08 (default), Ba (Ratio of forward scatter irradiance to the total irradiance): 0.85 (default), and Albedo: 0.1 (usually for lakes 0.08 – 0.12). From resulting Direct Beam hourly values, I obtained daily average values for studied time period, July 1st – August 15th. I used the calculated theoretical clear sky solar radiation (TCSR) without adjustments, because there are no mountains, trees, buildings, or anything what would cause significant shading on the lakes. The

TCSR does not account for cloud cover and, therefore, does not correspond to ground monitored solar radiation levels during overcast days.

The model proposed by Kettle et al. (2004) assumes that lake surface temperatures are predominantly controlled by an exponentially smoothed version of the local air temperature. Change in lake surface temperatures (T_W) is given by following equations:

$$\frac{dT_w}{dt} = k(T_a - T_w) \qquad \textbf{(1)}$$

$$T_{w,t} = \left(1 - e^{-k\Delta t}\right)T_{a,t} + e^{-k\Delta t}\, T_{w,t-\Delta t} \qquad \textbf{(2)}$$

$$f\left(T_{a,t}\right) = \alpha T_{a,t} + (1-\alpha) f(T_{a,t-\Delta t}) \qquad \textbf{(3)} \quad \text{where } \alpha = 1 - e^{-k\Delta t}$$

$$T_w = a + bf(T_a) + c\, TCSR \qquad \textbf{(4)}$$

Where **t** = time, **Δt** = one day increments (=1), $\mathbf{T_a}$ = air temperature, **k** = constant heat exchange coefficient with inverse dimension of time, ***f*** = exponential smoothing function, **α** = smoothing parameter **(°C^{-1})**, **TCSR** = Theoretical clear-sky solar radiation, **a** = possibly a function of the heat energy stored within the lake, "base level temperature", **b** = the air temperature coefficient, it controls the sensitivity of the lake surface temperature to air temperature, **c** = the theoretical clear-sky solar radiation coefficient.

$$\frac{dT_w}{dt} = k(T_a - T_w) \qquad \textbf{(1)}$$

Constant **k** was the outcome of the first equation. For left side of (1), I subtracted daily water temperature measured on day **t+1** from $\mathbf{T_W}$ measured on day **t-1** and divided by two. Thus I obtained average difference in water temperature, which gave a better fit for modeling than when I tried a difference in water temperature of two consecutive days **(t-1) – t**. **α** was then calculated from **k** by a simple relationship $\boldsymbol{\alpha = 1 - e^{-k\Delta t}}$. The smoothing parameter **α** describes the rate of response of the water temperature to changes in air temperature.

$$T_{w,t} = \left(1 - e^{-k\Delta t}\right)T_{a,t} + e^{-k\Delta t}\, T_{w,t-\Delta t} \qquad \textbf{(2)}$$

Constant heat exchange coefficient with inverse dimension of time **k** determined in (1) was inserted into (2). (2) actually represents the equation (1) integrated over time. Resulting $\mathbf{T_{W,t}}$ is necessary input into (4) as to determine coefficients **a**, **b**, and **c.**

$$\boldsymbol{f(T_{a,t}) = \alpha T_{a,t} + (1-\alpha) f(T_{a,t-\Delta t})} \qquad \textbf{(3)} \qquad \text{where } \alpha = 1 - e^{-k\Delta t}$$

The model assumes that $\mathbf{T_W}$ is related to air temperature by a smoothing function $\boldsymbol{f}$, such that $\mathbf{T_{W,t} = \boldsymbol{f}(T_{a,t})}$. Third equation finds the smoothing function $\boldsymbol{f}(\mathbf{T_{a,t}})$ with use of the smoothing parameter $\boldsymbol{\alpha}$. By smoothing the air temperature, improvements are achieved in model fit. Reduction of the variance of the air temperature data and time delay incorporation are results of use of the smoothing function. Equation (3) was solved for daily time-steps by use of Excel. Column of cells was programmed according to (3), which was a quite challenging task because previous cells $\boldsymbol{f}(\mathbf{T_{a,\,t-\Delta t}})$ of the same result column were also input values for later cells $\boldsymbol{f}(\mathbf{T_{a,t}})$ in the same column. Values for model development started on June 22nd 2011 as to make sure that values are not significantly biased for the time period of July 1st – August 15th and give the best possible fit.

$$\boldsymbol{T_w = a + bf(T_a) + c\,TCSR} \qquad \textbf{(4)}$$

Because air temperature does not fully explain changes in surface water temperature during summer months, **TCSR** needs to be incorporated especially to account for $\mathbf{T_W}$ consistently exceeding $\mathbf{T_a}$ in summer. To estimate modeling constants **a**, **b**, and **c** for each lake, and because $\mathbf{T_W}$ can be modeled satisfactory as a linear combination of exponentially smoothed $\mathbf{T_a}$ and the **TCSR**, I used multiple linear regression of our data. This statistical analysis was conducted with use of software R, version 2.13.1. A code was programmed which resulted in obtaining constants **a**, **b**, and **c** for all water-bodies.

The outcome of fitting predictions to $\mathbf{T_W}$ measurements are the four model parameters: **a**, **b**, **c**, and $\boldsymbol{\alpha}$. Kettle et al. (2004) restrict the model to water temperatures above 4°C because of the water density anomaly. For more details on modeling, please refer to Kettle et al. (2004).

The procedure of model development was conducted three times, because I wanted to examine what set of input variables give the best fit. The first model included data on air temperature and solar radiation monitored at our small weather station on Devil's Lake shore. Second model included input data on air temperature monitored at the airport weather station and the theoretical clear sky solar radiation. The third model included data on air temperature monitored at the airport weather station and solar radiation measured by our small weather station (Table 2.2).

Table 2.2 Comparison of the three models. Each is driven by a different combination of datasets from various sources. DL represents a small weather station on Devil's Lake shore, KOTZ represents the Ralph Wien Memorial airport weather station in Kotzebue, and TCSR is the Theoretical Clear-sky Solar Radiation.

Model Type	Air Forcing	Radiation Forcing
1	DL	DL
2	KOTZ	TCSR
3	KOTZ	DL

The first model aimed to work with the most pertinent data for the source lakes as our weather station was right in their location and also measured the actual solar radiation. The second model is the model I used later for hindcasting because it works with a data source providing long-term air temperature data and theoretical solar radiation because the actual is not being long-term monitored. The third model aimed to reveal how significantly modeled values differ between those estimated with TCSR and those estimated with monitored solar radiation. Because I wanted to test how close our models are from monitored values, I made graphs and obtained the Root Mean Square Error (RMSE) statistics (in Excel =SQRT((SUM(T_w observed – T_w modeled)^2)/(n-1)). Surface water temperatures from 1985 until 2010 were hindcasted for each studied water-body by applying the parameters **a**, **b**, and **c** obtained from previous modeling. The past air temperature measurements were adjusted by α as to give $f(T_{a,t})$. Therefore, only equations (3) and (4) were used for hindcasting. The individual lake models which were used to hindcast could also be used to forecast the summer surface water temperatures with obtained predictions of air temperatures.

CHAPTER 3: DATA ANALYSIS AND RESULTS

3.1 Data evaluation

In order to understand the hydrological and thermal regimes of studied lakes, I focused on following phenomena and physical quantities and their changes: water temperature (surface and bed), air temperature, incoming solar radiation, precipitation, water depth and operation of water for treatment plant. Relationships between the precipitation, water depth, and management are found in section 2.1 Description of study area.

Thermal regimes of the studied water-bodies over the monitoring period

The surface (T_{ws}) and bed (T_{wb}) water temperatures in all four studied water-bodies were monitored during the time period of June 22nd- August 28th, 2011. I have observed the mean T_{ws} to be very similar for all water-bodies and range between 14.4 and 14.6°C with the lowest for Devil's Lake and the highest for Mosquito Lake (Table 3.1). The highest maximum daily average T_{ws} of 19.5°C was recorded on June 29th in Mosquito Lake. The lowest maximum daily average T_{ws} of 18.2°C was recorded also on June 29th in Vortac Lake. The maximum daily average T_{ws} also occurred on June 29th in Devil's Lake (18.6°C) and on June 28th in Lagoon (18.9°C). The lowest minimum daily average T_{ws} of 10.7°C was recorded on July 4th in Mosquito Lake. The highest minimum daily average T_{ws} of 11.6°C was recorded on August 25th in Vortac Lake. The minimum daily average T_{ws} also occurred on August 25th in Lagoon (11.5°C) and on July 4th in Devil's Lake (10.9°C). The maximum values usually occurred in July and the minimum values in June/ early July or August.

Table 3.1 Summary of the mean, maximum and minimum daily averages of surface water temperatures monitored in the four studied water-bodies during the time period of June 22nd- August 28th, 2011.

Water-body	Depth m	Area km²	Mean Tws °C	Max Tws °C	Min Tws °C
Devil's Lake	3.64	1.01	14.4	18.6	10.9
Vortac Lake	2.28	0.41	14.5	18.2	11.6
Mosquito Lake	1.56	1.48	14.6	19.5	10.7
Lagoon	1.99	3.88	14.5	18.9	11.5

The individual water-bodies varied in their ranges of daily mean surface water temperatures. The greatest range of 8.8°C was observed in Mosquito Lake, Devil's Lake's range was 7.7°C, Lagoon's was 7.4°C, and the lowest range of 6.6°C was recorded in Vortac Lake (Figure 3.1).

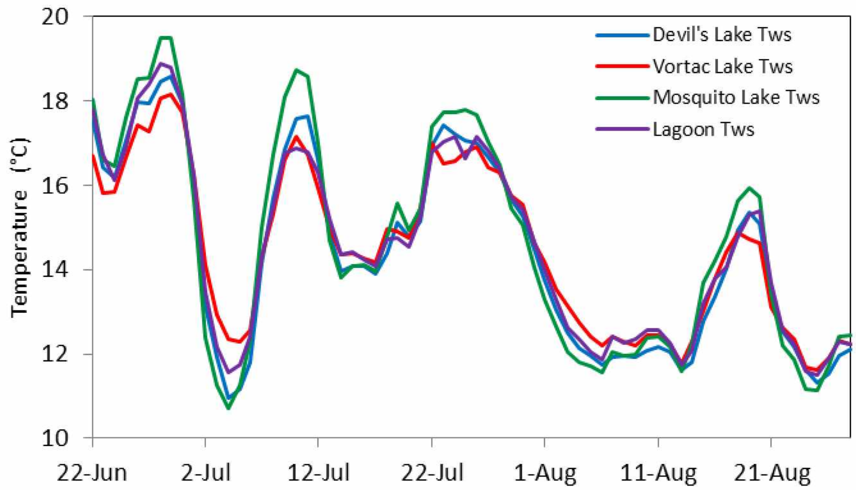

Figure 3.1 Daily means of surface water temperatures monitored in the four studied water-bodies during the time period of June 22nd-August 28th, 2011.

The mean T_{wb} were not as similar as the T_{ws} in the four water-bodies and ranged between 13.5 and 14.3°C with the lowest in Devil's Lake and the highest in Mosquito Lake (Table 3.2). All the maximum daily average T_{wb}'s were recorded on June 29th. The highest maximum daily average T_{wb} of 19.3°C was observed in Mosquito Lake. The lowest maximum daily average T_{wb} of 17.6°C was recorded in Devil's Lake. The monitored maximum daily averages gave a range of 1.7°C for the four water-bodies. The maximum daily average T_{wb} was in Vortac Lake 17.9°C and in Lagoon 18.3°C. The lowest minimum daily average T_{wb} of 10.7°C was recorded on July 4th in Mosquito Lake (the same date and temperature as T_{ws}). The highest minimum daily average T_{wb} of 11.5°C was recorded on August 25th in Vortac Lake. The monitored minimum daily averages gave a range of 0.8°C for the four water bodies. The minimum daily average T_{wb} also occurred on August 25th in Lagoon (11.4°C) and on July 4th in Devil's Lake (11.1°C). Devil's Lake showed a very interesting pattern as on July 4th the mean daily surface water temperature (10.9°C) was lower than the mean daily bed water temperature (11.1°C).

Table 3.2 Summary of the mean, maximum and minimum daily averages of bed water temperatures monitored in the four studied-water bodies during the time period of June 22nd- August 28th, 2011.

Water-body	Depth m	Area km²	Mean Twb °C	Max Twb °C	Min Twb °C
Devil's Lake	3.64	1.01	13.5	17.6	11.1
Vortac Lake	2.28	0.41	13.8	17.9	11.5
Mosquito Lake	1.56	1.48	14.3	19.3	10.7
Lagoon	1.99	3.88	14.0	18.3	11.4

The individual water-bodies varied in their ranges of daily mean bed water temperatures. The greatest range of 8.6°C was observed in Mosquito Lake, Devil's Lake's range was 6.5°C, Lagoon's was 6.9°C, and the lowest range of 6.4°C was recorded in Vortac Lake (Figure 3.2).

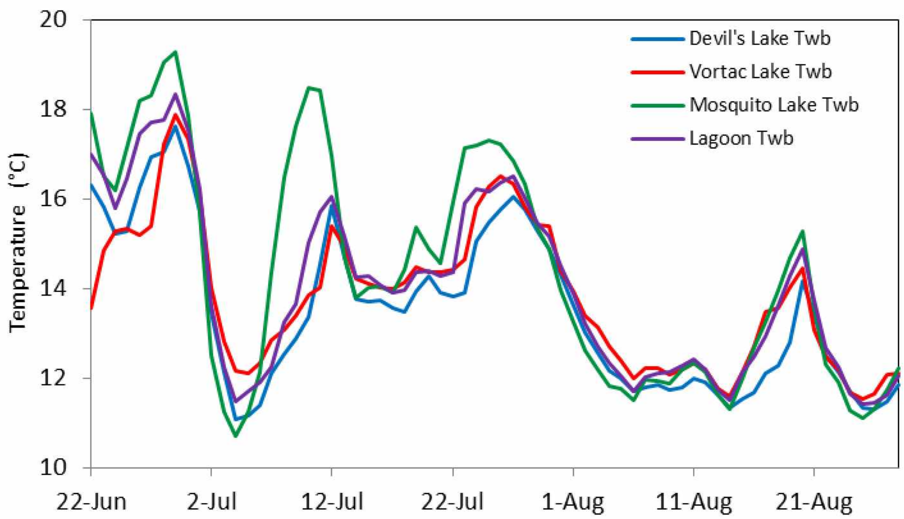

Figure 3.2 Daily means of bed water temperatures monitored in the four studied water-bodies during the time period of June 22nd-August 28th, 2011.

Effect of air temperature on water temperature and stratification

Water temperature is largely affected by air temperature through heat exchange flux on the water-air interface. The water depth is also a significant factor determining water temperature and stratification patterns. I monitored the water depth changes, as shown in section 2.1, air temperature and water temperatures near surface (10 cm depth) and at the lake bed. Sensors were deployed in places which we assessed to be near the maximum depth of each water-body.

Although the lakes are quite shallow, I observed different water temperatures at the surface and near the lake bed at times, which indicates thermal stratification. I have calculated the percentage of time each water-body was stratified during the monitoring period (June 22nd-August 28th, 2011). Because I did not find a standard definition which would give a specific temperature difference for considering a water-body as stratified, I defined a water-body as stratified when a temperature difference between mean daily T_{ws} and T_{wb} was equal or greater than 1°C. I decided for 1°C after reviewing my datasets and considering the lake depth and latitude. Devil's Lake was in total stratified for about one third of the monitoring period. Vortac Lake and Lagoon were stratified for about 20% of time and Mosquito Lake for only 9% (Table 3.3).

Table 3.3 Percentage of total time the studied water-bodies were stratified during the monitoring time period, June 22nd-August 28Th, 2011, the mean and maximum temperature differences between $\mathbf{T_{ws}}$ **and** $\mathbf{T_{wb}}$ during stratification, temperature decrease over 1m of depth, the number of stratification periods and their average duration.

Water-body	Percent of time stratified	Mean Strat T difference °C	Maximum T difference °C	Depth m	Δ T/ Depth °C/ m	Stratified #	Average duration of stratified days
Devil's Lake	34%	2.1	4.2	3.64	1.15	7	3.5
Vortac Lake	21%	2.1	3.3	2.28	1.45	6	2.5
Mosquito Lake	9%	1.5	1.7	1.56	1.09	2	3
Lagoon	19%	1.6	3.1	1.99	1.56	4	3.5

The mean temperature differences between daily mean T_{ws} and T_{wb} during the stratification periods were 2.1°C in Devil's and Vortac Lakes and 1.6°C and 1.5°C in Lagoon and Mosquito Lake respectively. The maximum temperature difference between daily mean T_{ws} and

T_{wb} of 4.2°C was recorded in Devil's Lake. The maximum temperature differences between daily mean T_{ws} and T_{wb} were in Vortac Lake and Lagoon about 3°C and in Mosquito Lake 1.7°C. These results logically correspond with the depth in which our sensors were located in each-water body; the deepest Devil's Lake was stratified for the longest period of time and had the highest maximum temperature difference between daily mean T_{ws} and T_{wb}. The shallowest Mosquito Lake was stratified for the shortest period of time and had the lowest maximum temperature difference between daily mean T_{ws} and T_{wb}. The highest ratio of the maximum temperature difference and depth was observed in Lagoon and Vortac Lake (about 1.5°C / 1 m). This ratio was about 1.2 in Devil's Lake and 1.1 in Mosquito Lake.

Devil's and Vortac Lakes experienced a stratified period 7 and 6-times respectively during the monitoring period. Lagoon had 4 periods of stratification and Mosquito Lake only 2. The duration of these stratification periods was similar for all water-bodies and ranged from 2.5 to 3.5 days. The unstratified periods varied substantially with the longest average of 20.7 days recorded in Mosquito Lake. Lagoon's average duration of unstratified periods was 11 days, Vortac Lake's 9 days and Devil's Lake's 6.5 days. The pattern in these findings also corresponds to the depth of each water-body.

I have calculated the temperature differences between the mean surface water temperatures for the entire monitoring period of each water body and the mean air

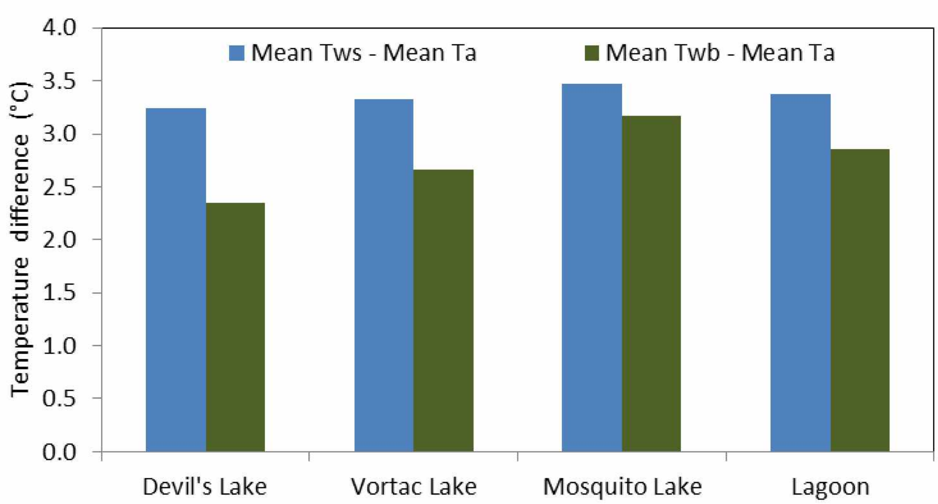

Figure 3.3 The temperature differences between the mean T_{ws} and mean T_a , and between the mean T_{wb} and mean T_a for the entire monitoring time period and each water-body.

temperature of the same time period (Figure 3.3). The temperature differences of mean T_{ws} and mean T_a were quite similar in all water-bodies ranging between 3.2 and 3.5°C. The temperature differences between the mean bed water temperatures for the entire monitoring period of each water body and the mean air temperature of the same time period were calculated as well. The temperature differences of mean T_{wb} and mean T_a gave a wider range of 2.4 - 3.2 °C (Table 3.4). Such results can also be related to the depth of each water-body.

Table 3.4 The temperature differences between mean T_{ws} and T_a and between T_{wb} and T_a calculated for the entire monitoring period, June 22nd-August 28th, 2011.

Water-body	Mean Tws - Mean Ta °C	Mean Twb - Mean Ta °C
Devil's Lake	3.2	2.4
Vortac Lake	3.3	2.7
Mosquito Lake	3.5	3.2
Lagoon	3.4	2.9

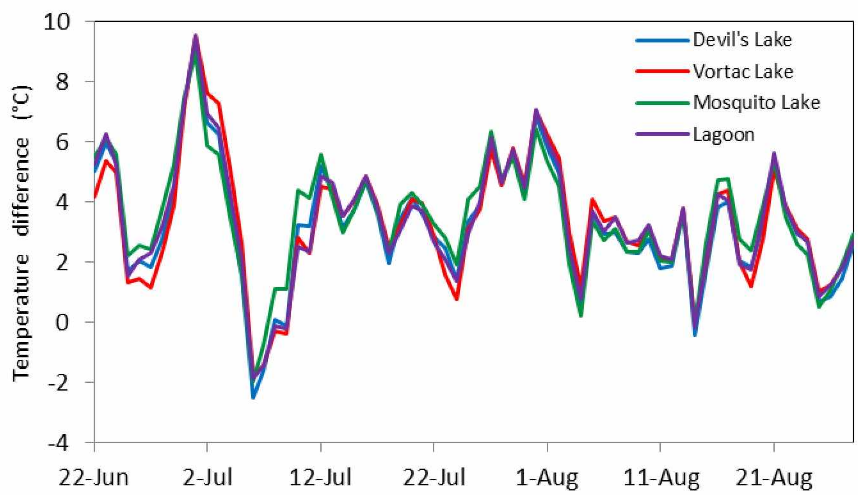

Figure 3.4 Temperature differences between daily means of T_{ws} of each water-body and T_a during the monitoring time period.

Temperature differences between the daily mean surface water temperatures and daily mean air temperatures gave a range of -2.5°C to 9.6°C. The low and high extremes were recorded on July 6th in Devil's Lake and on July 1st in Lagoon respectively (Figure 3.4). The following graphs (Figure 3.5) show the stratification patterns of each water-body. Daily mean surface and bed water temperatures were related to daily mean air temperatures. Generally, the delay between air temperature peaks and water temperature peaks was between one and three days.

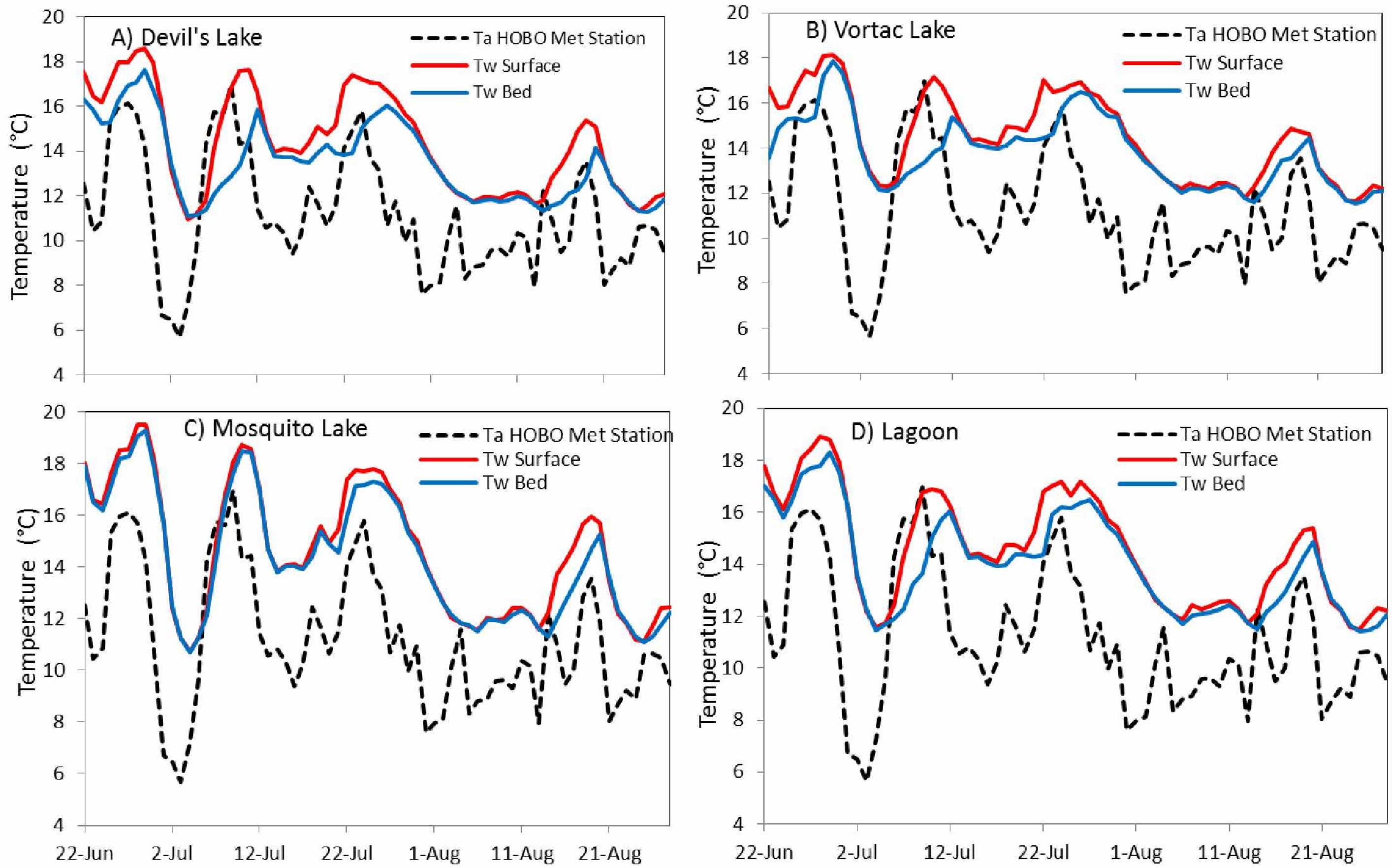

Figure 3.5 Water temperature stratification in (A) Devil's Lake, (B) Vortac Lake, (C) Mosquito Lake, and (D) Lagoon showing surface water temperatures and bed water temperatures in relation to changing air temperatures.

In Devil's Lake, stratification ($T_{ws} - T_{wb} \geq 1°C$) occurred during following time periods: June 22nd, June 25th-30th (with one day of $T_{ws} - T_{wb} < 1°C$), July 7th-11th, July 19th-26th (with one day of $T_{ws} - T_{wb} < 1°C$) and August 15th-19th. The highest difference between T_{ws} and T_{wb} of 4.2°C was recorded on July 10th, 2011. In Vortac Lake, stratification ($T_{ws} - T_{wb} \geq 1°C$) occurred during following time periods: June 22nd, June 25th-27th, July 7th-11th, July 21st-23rd, and August 16th-18th (with one day of $T_{ws} - T_{wb} < 1°C$). The highest difference between T_{ws} and T_{wb} of 3.3°C was recorded on July 10th, 2011. In Mosquito Lake, stratification ($T_{ws} - T_{wb} \geq 1°C$) occurred during following time periods: June 22nd, and August 15th-19th. The highest difference between T_{ws} and T_{wb} of 1.7°C was recorded on August 15th, 2011. In Lagoon, stratification ($T_{ws} - T_{wb} \geq 1°C$) occurred during following time periods: June 28th, July 7th-11th, July 22nd-23rd, and August 15th-19th. The highest difference between T_{ws} and T_{wb} of 3.1°C was recorded on July 9th, 2011.

Table 3.5 Time periods with decreasing/increasing air temperature trends during summer 2011.

Time Period 2011	Length of Time Period (Days)	Δ Ta (°C)
June 22-23	2	-2.1
June 24-27	4	5.7
June 28-July 3	6	-10.4
July 4-9	6	11.3
July 10-16	7	-7.6
July 17-24	8	6.4
July 25-31	7	-8.2
August 1-4	4	4.0
August 5	1	-3.3
August 6-12	7	1.8
August 13	1	-2.2
August 14	1	4.3
August 15-16	2	-2.8
August 17-19	3	4.1
August 20-21	2	-5.5
August 22-26	5	2.6
August 27-28	2	-1.2

The water temperature differences between the lake surface and bed, and the duration and frequency of stratification periods were closely related to changes in air temperature (Figure 3.5, Table 3.5) and the depth of studied water-bodies (Table 3.3). The water temperature changes occurred with a delay of one to three days after changes in air temperature. The air temperature changes over distinct time periods with decreasing and increasing trends gave an interesting pattern with generally longer drop/upturn periods characteristic by larger T_a changes occurring in June and July and shorter drop/upturn periods characteristic by smaller T_a changes occurring in August. Stratification was especially present during increases in temperature. During periods of decreasing temperature, lakes experienced mixing. We questioned if storm events and associated wind which caused turbulence in the water were partially responsible for the mixing.

The daily mean wind velocities during the monitoring period were related to the temperature differences between daily mean T_{ws} and T_a and between daily mean T_{ws} and T_{wb} of Devil's Lake. There is an interesting pattern between the blue line (T_{ws} – T_{wb}) and the green dashed line (wind speed). The four major peaks on the blue line indicate stratification periods – substantial temperature differences between the surface and bed water temperatures. These peaks are noticeably correlated to time periods with low wind speed (Figure 3.6).

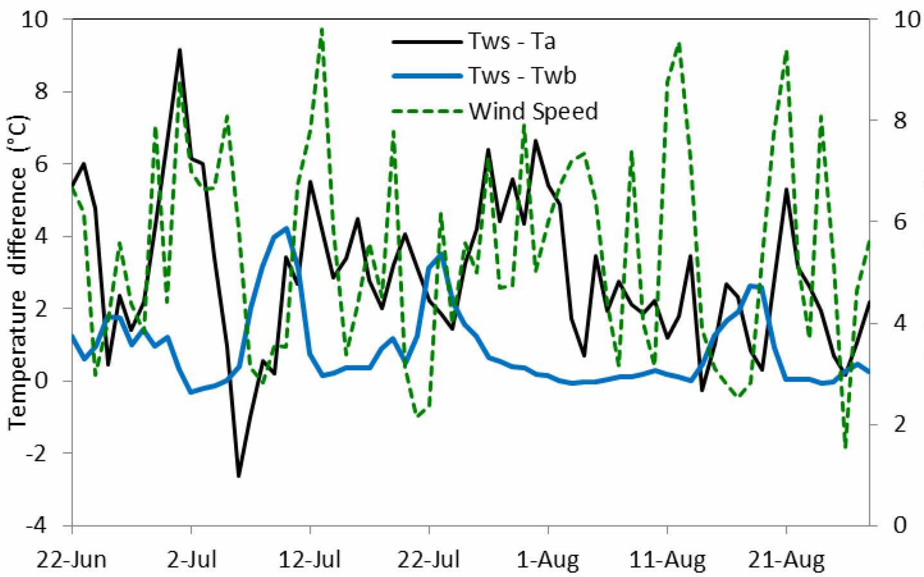

Figure 3.6 Daily mean wind speed related to temperature differences between daily mean T_{ws} and T_a and between daily mean T_{ws} and T_{wb} during June 22nd-August 28th, 2011.

In order to assess the influence of wind on lake thermal regimes in a greater detail, I have selected two shorter time periods for closer investigation. The one selected period of water warming was July 5th – July 10th and the one period of cooling was August 1st- August 6th. Both time periods were of the same length – 6 days. Following graphs (Figures 3.7 and 3.8) are based on monitored hourly data of wind speed, air temperature, surface water temperature and bed water temperature. The meteorological quantities were obtained from the Kotzebue airport weather station and the data on hourly water temperatures were measured in Devil's Lake.

The warming time period (Figure 3.7) clearly shows development of a thermal stratification in Devil's Lake. Interestingly, in the beginning of this time period, the T_{wb} was higher than T_{ws}. The bed and surface temperatures were equal on July 6th at 10 am and then the thermal stratification started to develop with more rapid surface temperature warming than the warming of the lake water by its bed. The mean T_{wb} over this warming period was 12.3°C and the mean T_{ws} was 14.5°C. The mean T_a was 14.3 °C and the mean wind speed was 4.4 m/s.

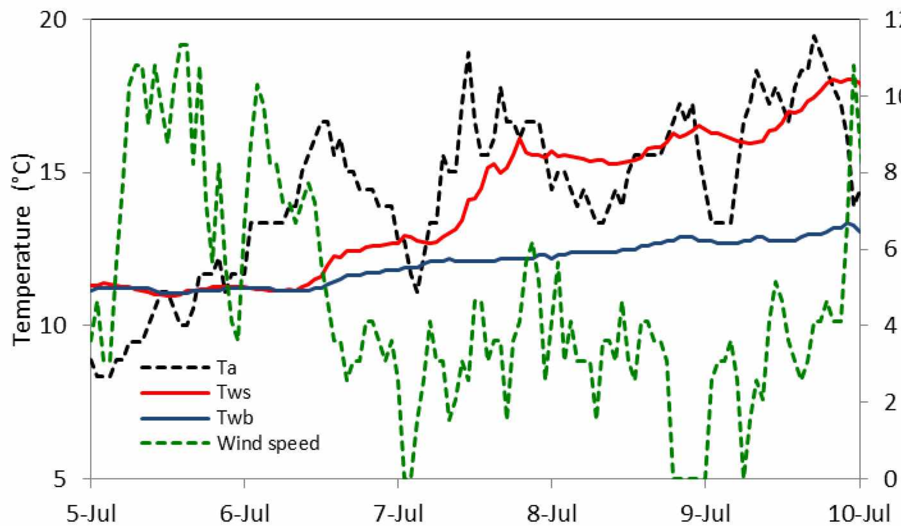

Figure 3.7 Surface water temperature and bed water temperature measured in hourly intervals in Devil's Lake related to changes in air temperature and wind speed during a warming time period of July 5th-July 10th, 2011.

The cooling time period (Figure 3.8) clearly shows a period of mixing in Devil's Lake. The bed and surface water temperatures were very similar with the mean of both, T_{wb} and T_{ws}, of 12.5°C. The mean T_a was 9.5 °C and the mean wind speed was 6.4 m/s.

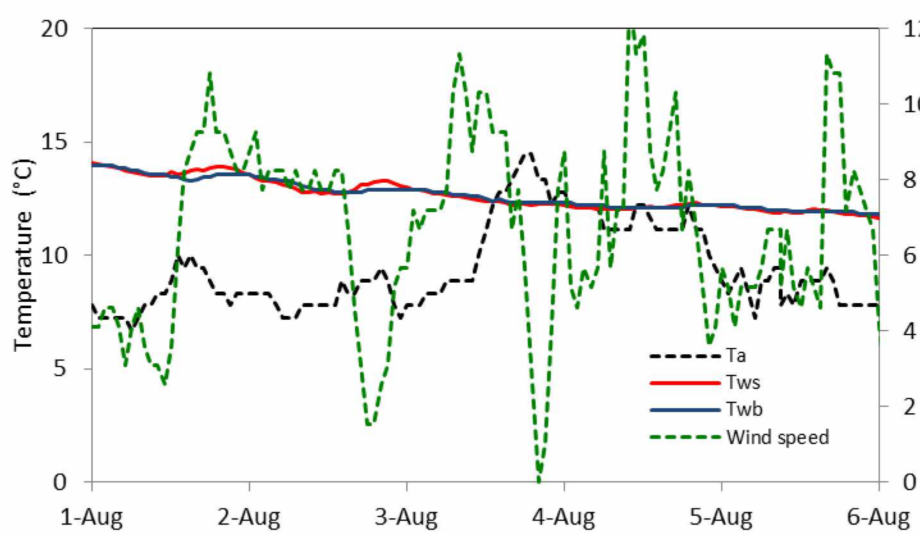

Figure 3.8 Surface water temperature and bed water temperature measured in hourly intervals in Devil's Lake related to changes in air temperature and wind speed during a cooling time period of August 1st- August 6th, 2011.

Correlating air temperatures from Devil's Lake and Kotzebue airport weather stations

For hindcasting and modeling purposes, I used long term air temperature measurements monitored at the proximate Ralph Wien Memorial Airport. To validate the use of the air temperature data from the airport weather station for modeling and hindcasting, these values were correlated with air temperature levels measured by Devil's Lake weather station. T_a recorded at the airport was statistically slightly higher than T_a recorded at Devil's Lake (Figure 3.9). The T_a values had least variation in the lowest range (6-9°C) and the most variation in the highest range (13-17°C). T_a values were more similar in July than in August (Figure 3.10). R^2 for comparison of the two datasets was 98.5% and RMSE was 0.56°C which gave me confidence to use the long term data on air temperature from the Kotzebue airport weather station.

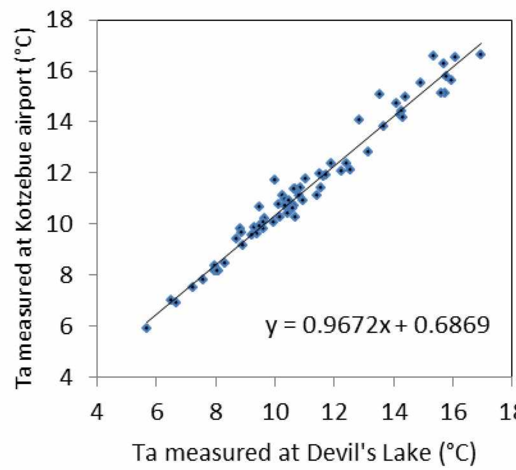

Figure 3.9 Correlation of air temperature measured at the Kotzebue airport weather station with temperature measured by our small HOBO weather station at Devil's Lake shore.

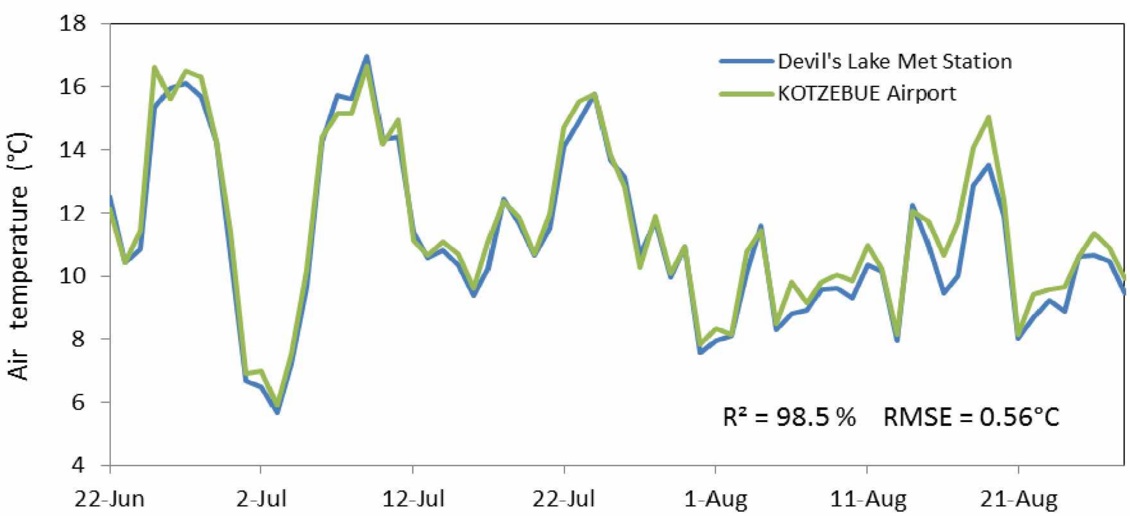

Figure 3.10 Air temperatures monitored by a weather station at Devil's Lake shore in comparison to air temperatures measured by the Kotzebue airport weather station between June 22nd and August 28th, 2011.

Effect of solar radiation on water temperature

Solar radiation is also a significant factor determining water temperature. I measured solar radiation at a weather station on Devil's Lake shore. Model by R. E. Bird (Bird & Hulstrom 1981) was also used to determine the Theoretical Clear-Sky Solar Radiation (TCSR) for the Kotzebue area. TCSR was calculated because data on real incoming solar radiation have not been monitored at the Ralph Wien Memorial Airport in Kotzebue. TCSR was then used for modeling and hindcasting purposes although it did not correspond with observed values of solar radiation very much (R^2 = 0.13 – no linear correlation) (Figures 3.11 and 3.12). TCSR represents the estimated highest possible values of solar radiation for Kotzebue area during the monitoring time period in summer 2011. Because of the presence of cloud cover, atmospheric attenuation, humidity, aerosols, ozone, etc., the observed values are significantly lower than TCSR.

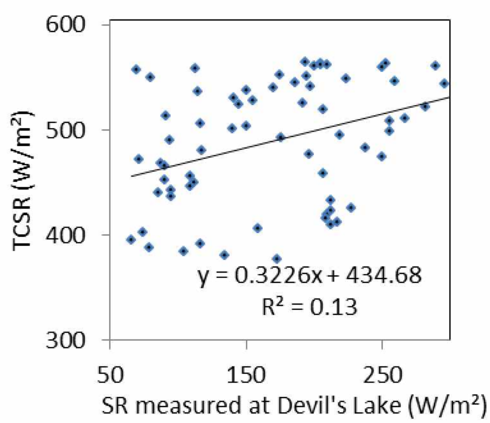

Figure 3.11 Correlation of measured solar radiation at Devil's Lake shore with the calculated Theoretical clear-sky solar radiation.

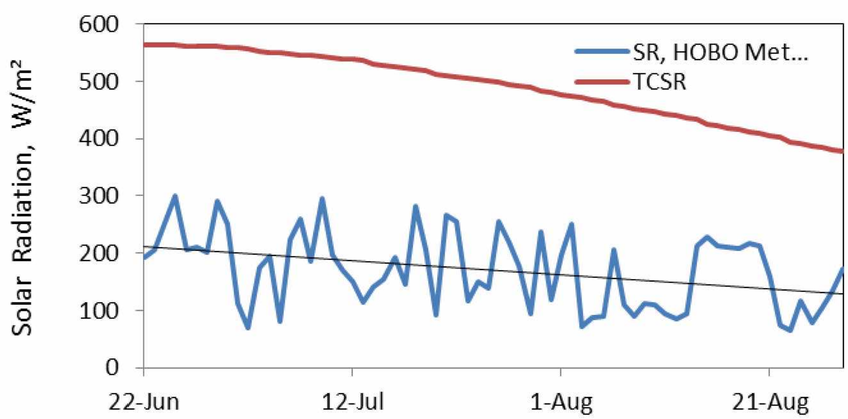

Figure 3.12 Comparisons of measured solar radiation (SR, HOBO) and calculated Theoretical clear-sky solar radiation (TCSR) for the time period of June 22nd – August 29th, 2011.

Additionally, air temperature carries some of the observed solar radiation information, and therefore, the TCSR and measured incoming solar radiation do not need to closely correlate for the modeling and hindcasting purposes. Following graph (Figure 3.13) shows the relationship.

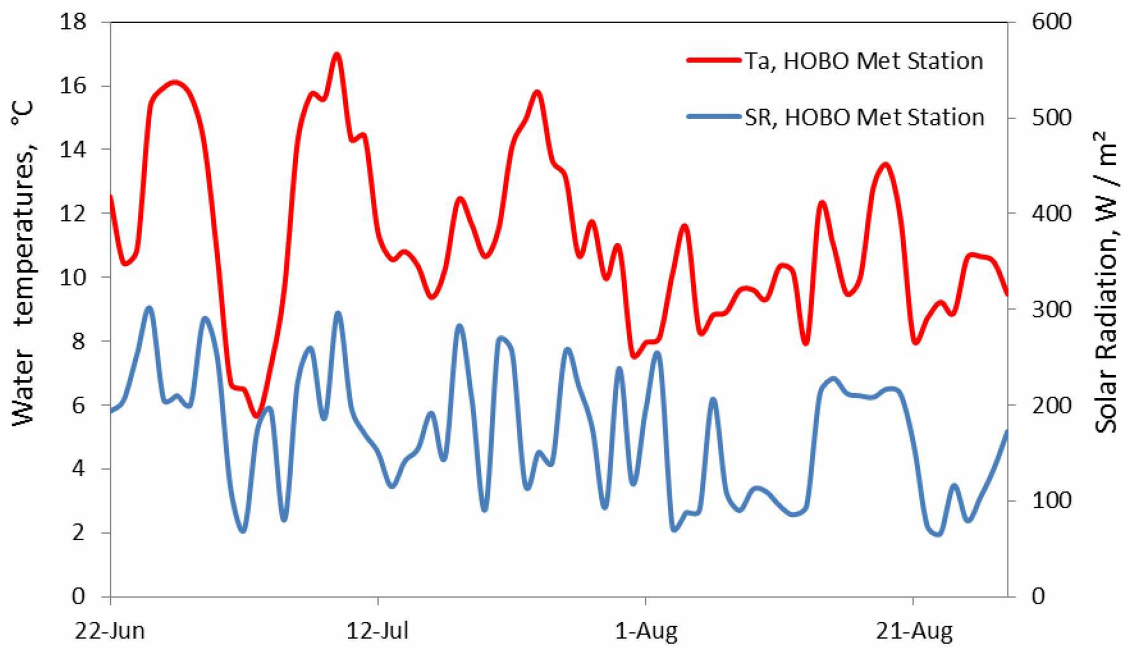

Figure 3.13 Graph shows the air temperature and solar radiation, both measured at Devil's Lake weather station in summer 2011.

3.2 Data modeling

An empirical model was developed for all studied water-bodies based on formulas given by Kettle et al. (2004). Three different models were compared each operating with different combination of input datasets (Figure 3.14). Following input data were used for **Model 1**: 1) air temperature data acquired by Devil's Lake met station in summer 2011, 2) solar radiation acquired by Devil's Lake met station in summer 2011, and 3) surface water temperatures monitored at each studied water-body. **Model 2**: 1) air temperature data observed at the Ralph Wien Memorial Airport in Kotzebue in summer 2011, 2) Theoretical Clear-Sky Solar Radiation calculated for Kotzebue area, and 3) surface water temperatures monitored at each studied water-body. **Model 3**: 1) air temperature data observed at the Ralph Wien Memorial Airport in Kotzebue in summer 2011, 2) solar radiation acquired by Devil's Lake met station in summer 2011, and 3) surface water temperatures monitored at each studied water-body (Table 2.2). Correlation function was used to estimate R^2, the coefficient of determination – the proportion of variability of y explained by x; and RMSEs were calculated for each model (Table 3.6). All R^2 were above 80%, which means more than 80% of variability in modeled T_{ws} was explained by observed T_{ws}; and although Model 2 had generally the lowest R^2 and the highest RMSE of the three models, it was used later for hindcasting because it calculates with TCSR and Kotzebue airport air temperature which were data available for estimates of past surface water temperatures.

Table 3.6 RMSE and R^2 for each of the three models developed for all four studied water-bodies.

	MODEL 1		MODEL 2		MODEL 3	
	RMSE (°C)	R^2	RMSE (°C)	R^2	RMSE (°C)	R^2
Devil's Lake	0.735	88.0%	0.781	86.6%	0.730	87.6%
Vortac Lake	0.616	87.9%	0.631	87.2%	0.701	83.1%
Mosquito Lake	0.724	90.8%	0.747	90.1%	0.678	91.7%
Lagoon	0.687	87.8%	0.724	86.1%	0.659	87.9%

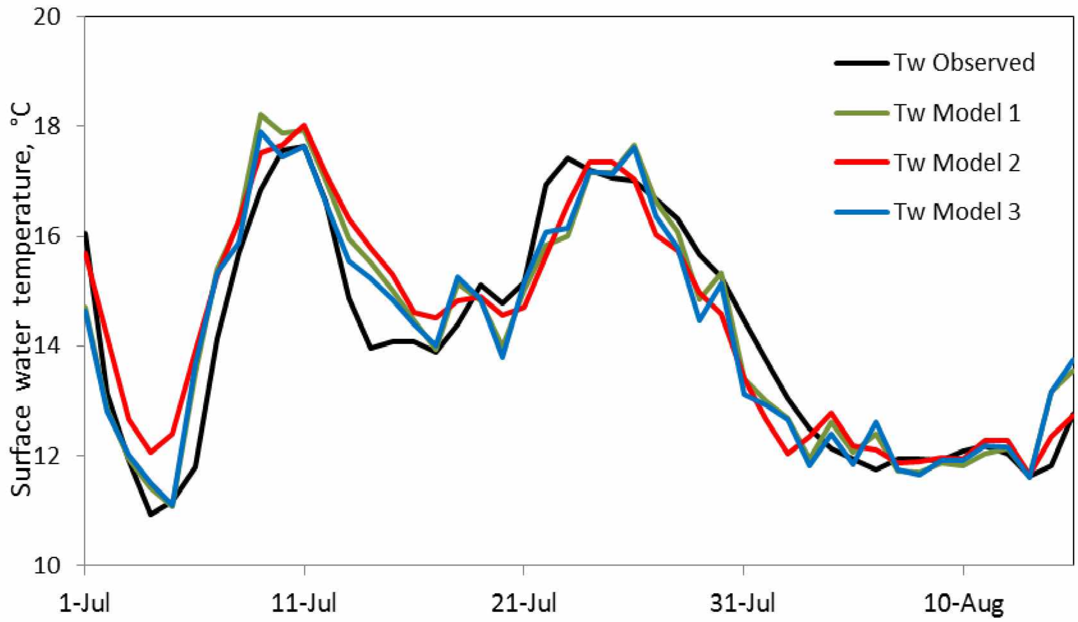

Figure 3.14 Comparisons of measured surface water temperatures and the three models developed for Devil's Lake and time period July 1st – August 15th, 2011.

Constants **k** and **α** were determined for smoothing the temperature function and parameters **a**, **b**, and **c** were estimated for each water-body. The values for Model 2 which was used later for hindcasting are listed in Table 3.7.

Table 3.7 Parameters estimated with use of Model 2 for all four studied water-bodies.

Water-body	Smoothing parameter, α (°C^{-1})	Intercept, a (°C)	Air temperature coefficient, b	Solar radiation coefficient, c (°C m^2 W^{-1})	R^2
Devil's Lake	0.247	-4.521	1.223	0.010	0.84
Vortac Lake	0.187	-3.552	0.999	0.014	0.78
Mosquito Lake	0.297	-4.876	1.318	0.009	0.88
Lagoon	0.237	-3.572	1.168	0.010	0.85

Model based on TCSR and Kotzebue airport air temperature measurements (Model 2) was applied to Devil's Lake using determined coefficients **a**, **b** and **c** (Figure 3.15). I made similar graphs for all the studied water-bodies and generally came to a conclusion that the model

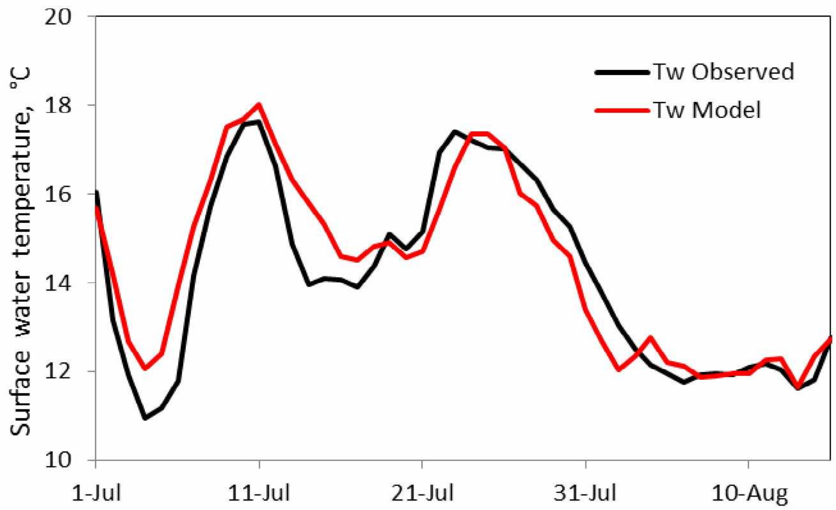

Figure 3.15 Modeled Devil's Lake surface water temperatures based on TCSR and Kotzebue Airport air temperature (Model 2) in comparison to the observed surface temperatures.

overestimated the surface water temperatures until about July 18th-20th (July 19th in case of Devil's Lake). Then modeled values were largely underestimating the surface water temperatures for the rest of July and then were about right for the ten last days of the studied period (Figure 3.16).

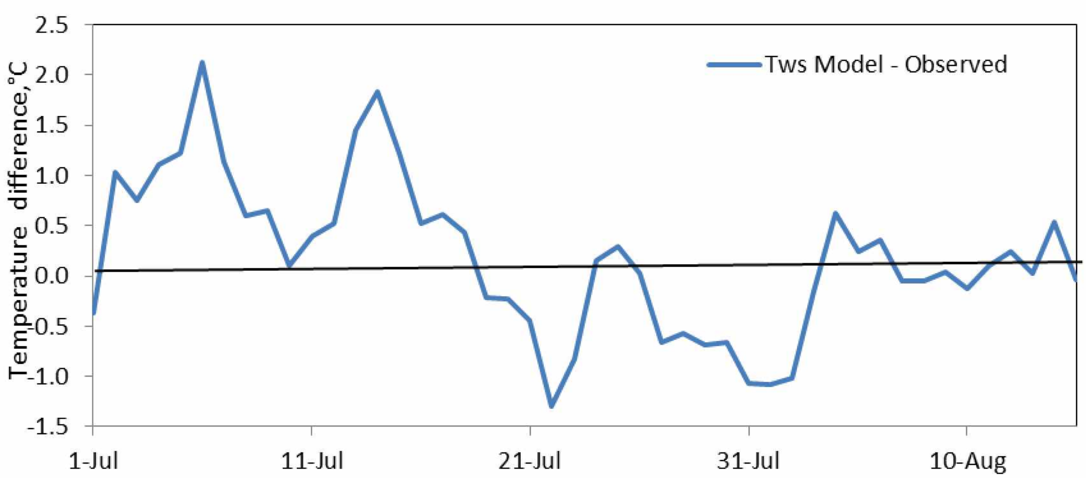

Figure 3.16 Temperature difference between modeled and observed surface water temperatures of Devil's Lake during the time period of July 1st – August 15th, 2011.

It is probably due to the fact that water has the ability to store heat. Model parameters **a**, **b** were **c** are constant for the studied period of time which did not allow considering that water has stored more heat by the end of July – beginning of August, than it had stored in the beginning of July. To support this interpretation, I have conducted a basic statistical analysis of the three distinct time periods, first being July 1st – 19th, second July 20th – August 2nd, and third August 3rd – 15th (Table 3.8).

Table 3.8 Difference between averages of the estimated Devil's Lake surface water temperatures and observed temperatures, R^2 and RMSE for three time periods.

MODEL 2 Devil's Lake	Average Difference (°C)	R^2	RMSE (°C)
Period 1 July 1-July 19	0.80	0.91	1.04
Period 2 July 20 - Aug 2	-0.58	0.93	0.74
Period 3 Aug 3 - Aug 15	0.13	0.47	0.29

The average differences between modeled and observed T_{ws} values for each period were calculated. During the first period, modeled water temperature in Devil's Lake was on average 0.8°C higher than the observed value. During the second period, modeled water temperature was on average 0.6°C lower than the observed value. The average difference was the lowest for the third period; the modeled T_{ws} were on average only 0.1°C higher than observed T_{ws}. The model provided the best estimates for the third period, although the R^2 statistic showed the worst fit. R^2 is the square of the sample correlation coefficient between the outcomes and their predicted values. From the graph above (Figure 3.15), it is apparent that lines for modeled and observed values are more parallel, thus correlated, during first and second periods as opposed to the third period. However, the model gives the best fit during the third period and RMSE confirms that. I obtained very similar results for the other three studied water- bodies.

3.3 Hindcasting

The models for hindcasting had to be based on data which were available for conducting the past estimates; therefore, I used historical data on air temperature measured at the Kotzebue airport weather station since 1985 and I kept TCSR constant for all years. I used lake specific model parameters (Table 3.6) which I determined during the model development phase of this study.

I have hindcasted thermal regimes for each of the four water-bodies during the summer time period of July 1st – August 15th for years 1985 – 2010. Then I have calculated mean surface water temperature for each lake and year, and extracted annual maximum and minimum daily mean values during that time period. I compared these values in following graphs. The mean surface water temperatures ranged between 12.2°C (Devil's Lake in 2000) and 19.7°C (Mosquito Lake in 2004) (Figure 3.17). The three coldest years were 2000, 2006 and 2003 with mean temperatures below 14°C for most of the water-bodies. The four warmest years were 2004, 1990, 2009 and 2007 with mean temperatures above 17°C. Individually, Devil's Lake's mean T_{ws} range was 12.2°C - 19.2°C (7°C), Vortac Lake's was 12.8°C - 18.6°C (5.8°C), Mosquito Lake's was 12.2°C – 19.7°C (7.5°C), and Lagoon's was 12.4°C – 19.1°C (6.7°C).

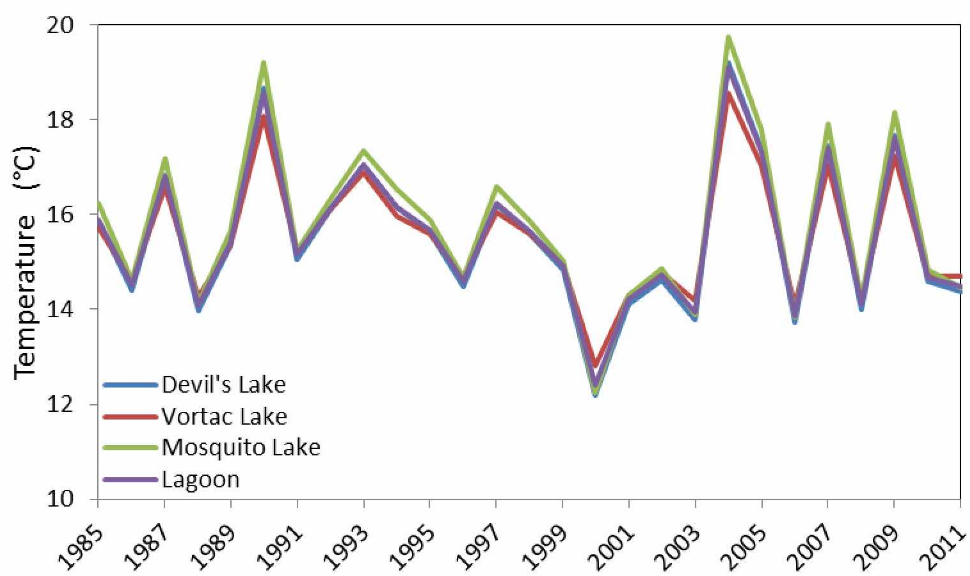

Figure 3.17 Hindcasted mean surface water temperatures of all studied water-bodies for each year since 1985 – 2010 and the time period of July 1st – August 15th.

The maximum daily mean surface water temperatures were determined for each year's time period of July 1st- August 15th (Figure 3.18). Mosquito Lake had the highest average value of the maximum daily mean T_{ws} of 20.6°C hindcasted for 1985-2010. Devil's Lake followed with 19.6°C, Lagoon with 19.4°C and Vortac Lake had the lowest value of 18.5°C in the same

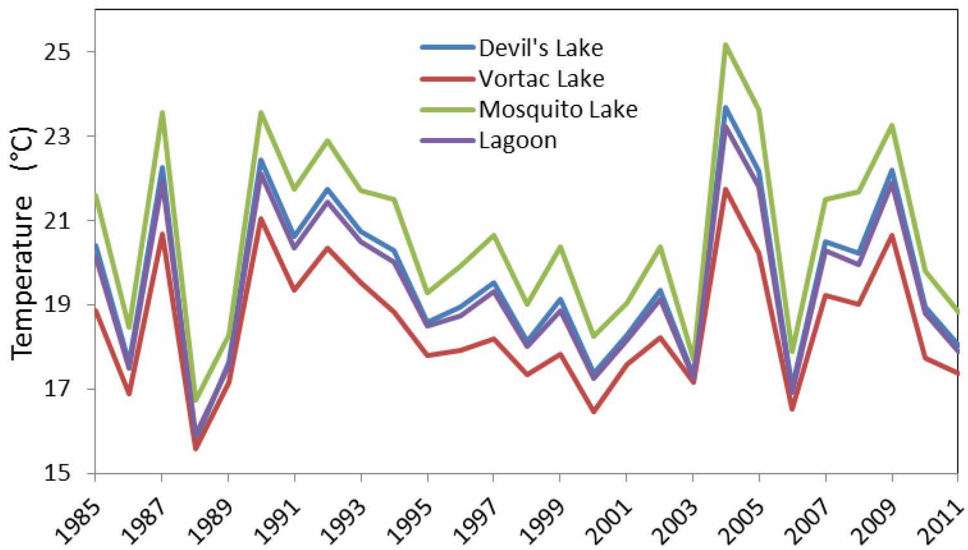

Figure 3.18 Hindcasted maximum surface water temperatures of all studied water-bodies for each year since 1985 – 2010 and the time period of July 1st – August 15th.

category. The lowest maximum daily mean T_{ws} of 15.6°C was hindcasted in 1988 and the highest maximum daily mean T_{ws} of 25.2°C was hindcasted in 2004. Individually, Devil's Lake's maximum daily mean T_{ws} range was 15.8°C – 23.7°C (7.9°C), Vortac Lake's was 15.6°C – 21.7°C (6.1°C), Mosquito Lake's was 16.7°C – 25.2°C (8.5°C), and Lagoon's was 15.9°C – 23.2°C (7.3°C).

The minimum daily mean surface water temperatures were determined for each year's time period of July 1st- August 15th (Figure 3.19). Mosquito Lake had the lowest average value of the minimum daily mean T_{ws} of 11°C hindcasted for 1985-2010. Devil's Lake followed with 11.4°C, Lagoon with 11.7°C and Vortac Lake had the highest value of 12.5°C in the same category. The lowest minimum daily mean T_{ws} of 6.6°C was hindcasted in 2002 and the highest minimum daily mean T_{ws} of 16.7°C was hindcasted in 2004. Individually, Devil's Lake's minimum daily mean T_{ws} range was 7.5°C – 16.4°C (8.9°C), Vortac Lake's was 9.8°C – 16.7°C (6.9°C), Mosquito Lake's was 6.6°C – 16°C (9.4°C), and Lagoon's was 8°C – 16.5°C (8.5°C).

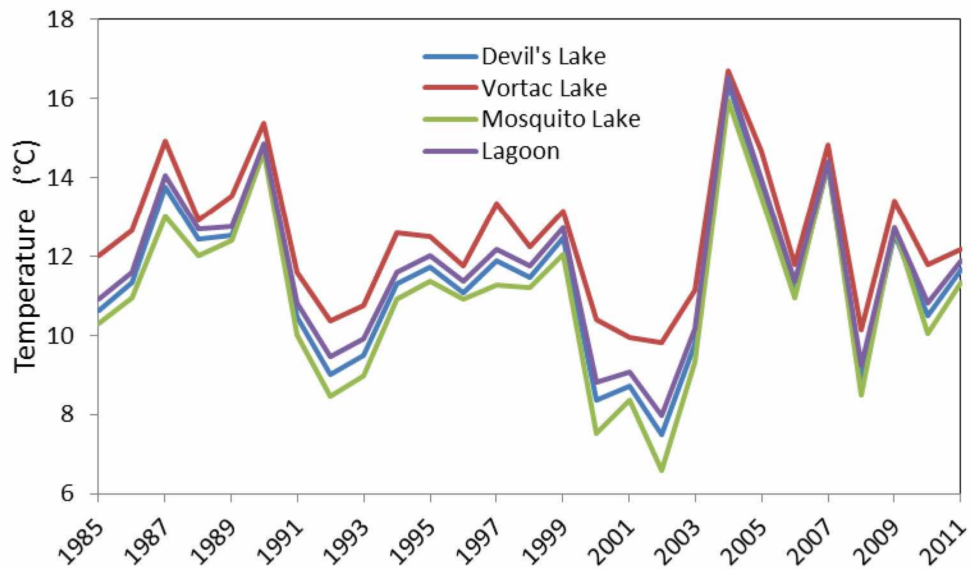

Figure 3.19 Hindcasted minimum surface water temperatures of all studied water-bodies for each year since 1985 – 2010 and the time period of July 1st – August 15th.

Generally, the ranges were the narrowest in case of the mean T_{ws} of the hindcasting period with an average of 6.8°C for all four water-bodies. The widest ranges were in case of the minimum daily mean T_{ws} with an average of 8.4°C for all four water-bodies. The range of the maximum daily mean T_{ws} had an average of 7.5°C for all four water-bodies. Individually, Mosquito Lake gave the widest range and Vortac Lake gave the lowest range in all cases.

I was also interested if there is any pattern in what particular day of the studied time period the maximum and minimum surface water temperatures occurred. In following graphs, the y-axis shows the date of maximum and minimum surface water temperatures for every year (Figure 3.20). The minimum daily mean T_{ws} values fell either into first two weeks of July or last two weeks in August and the maximum values largely happened in July.

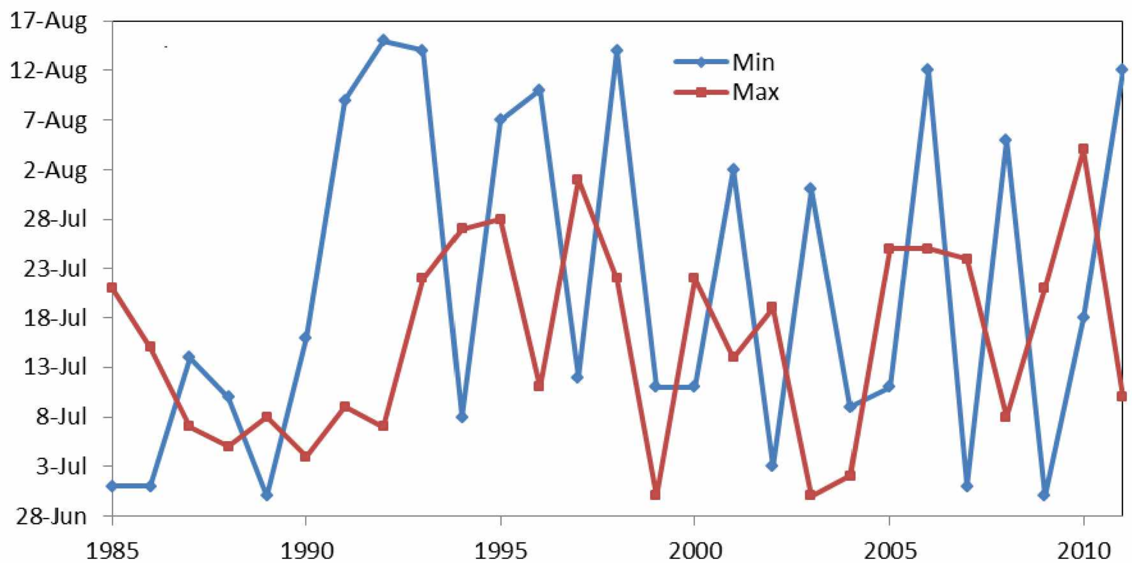

Figure 3.20 Distribution of minimum and maximum surface water temperatures over the studied time period.

The minimum daily mean surface water temperatures were largely distributed between the first two weeks in July (beginning of the hindcasting time period) and the first two weeks in August (end of the hindcasting time period). The years with "early" minimums were: 1985, 1986, 1989, 2007, and 2009. The years with "late" minimums were: 1992, 1993, 1998, 2006, and 2011. The maximum daily mean surface water temperatures were largely distributed between the first two weeks in July (beginning of the hindcasting time period) and the last two weeks in July (middle of the hindcasting time period). The years with "early" maximums were: 1988, 1990, 1999, 2003, and 2004. The years with "mid-period" maximums were: 1993, 1998, 2000, 2002, and 2009. There were five years, during which hindcasting periods, minimum and maximum daily mean T_{ws} values both occurred in first two weeks in July. These were 1987, 1988, 1989, 1999, and 2004, and in 1988, the time difference between the maximum and minimum daily mean T_{ws} was only 5 days. On the other hand, in 1992, the time difference between the maximum and minimum was the largest, 39 days.

The mean hindcasted T_{ws} of each water-body were compared to mean T_a of each year's hindcasting time period. The following graph (Figure 3.21) shows that the mean T_{ws} and T_a

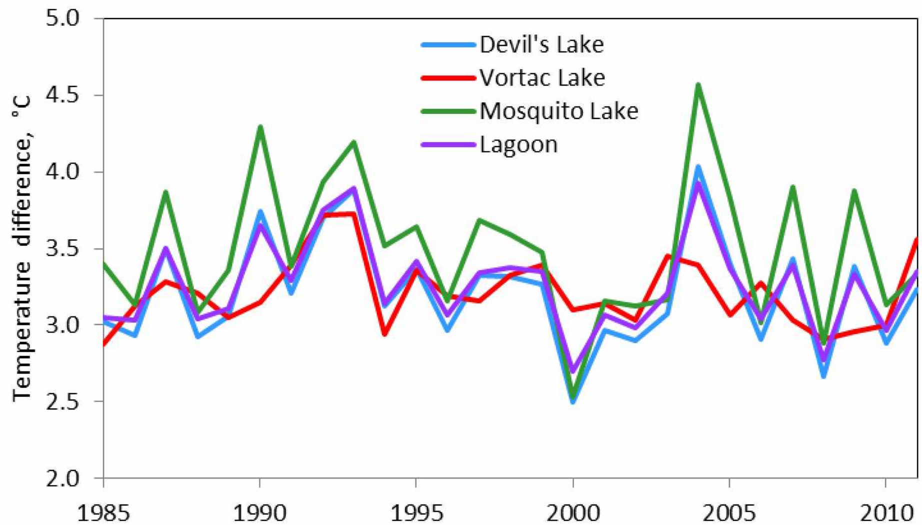

Figure 3.21 Temperature differences between hindcasted mean surface water (T_{ws}) and air (T_a) temperature for the July 1st-August 15th period from 1985 to 2011.

differences ranged between 2.5 and 4.6°C with the low extreme value belonging to Devil's Lake and the high extreme value belonging to Mosquito Lake. Mosquito Lake had the broadest T_{ws} - T_a range of 2.1°C (2.5- 4.6°C) Devil's Lake had a range of 1.5°C (2.5- 4°C), Lagoon had a range of 1.2°C (2.7- 3.9°C),and Vortac Lake had the narrowest range of 0.8°C (2.9– 3.7°C). In attempt to understand these results, a chart (Table 3.9) was constructed comparing various criteria. The blue cells highlight the five lowest values in each column and the red cells highlight the five highest values in each column. The only year with all red cells was 2004. The mean air temperature (July 1st - August 15th) of 15.2°C was absolutely the highest out of all years, the hindcasted mean surface water temperatures were also the highest for all four water-bodies (18.6 – 19.7°C). The differences between T_{ws} and T_a were among the five highest for all water-bodies (3.4 – 4.6°C) and the mean air temperature of April, May and June (AMJ) 2004 was 4°C, which was the highest and well above the mean AMJ T_a of -0.8°C for 1985-2011. Another year

Table 3.9 Comparisons of the mean air temperature, mean surface water temperatures and the differences between mean T_{ws} and T_a (all °C) of Devil's Lake (D), Vortac Lake (V), Mosquito Lake (M), and Lagoon (L) during the hindcasting time period of July 1st – August 15th each year with relation to mean air temperatures of April, May and June (AMJ), the months preceding our hindcasting time period. The blue and red colors represent the five smallest and the five greatest values, respectively, in each column.

Year	Mean Ta	AMJ Ta	D Tws	D Tws-Ta	V Tws	V Tws-Ta	M Tws	M Tws-Ta	L Tws	L Tws-Ta
1985	12.8	-6.6	15.9	3.0	15.7	2.9	16.2	3.4	15.9	3.0
1986	11.5	-3.4	14.4	2.9	14.6	3.1	14.6	3.1	14.5	3.0
1987	13.3	-1.4	16.8	3.5	16.6	3.3	17.2	3.9	16.8	3.5
1988	11.0	0.1	14.0	2.9	14.3	3.2	14.1	3.1	14.1	3.0
1989	12.3	-0.2	15.3	3.1	15.3	3.1	15.6	3.4	15.4	3.1
1990	14.9	0.7	18.7	3.7	18.1	3.2	19.2	4.3	18.6	3.7
1991	11.9	0.3	15.1	3.2	15.2	3.4	15.2	3.4	15.1	3.3
1992	12.4	-3.7	16.1	3.7	16.1	3.7	16.3	3.9	16.1	3.7
1993	13.2	0.8	17.0	3.9	16.9	3.7	17.4	4.2	17.1	3.9
1994	13.0	-1.5	16.1	3.1	16.0	2.9	16.5	3.5	16.2	3.1
1995	12.2	0.0	15.6	3.4	15.6	3.4	15.9	3.6	15.7	3.4
1996	11.5	-0.9	14.5	3.0	14.7	3.2	14.7	3.2	14.6	3.1
1997	12.9	1.3	16.2	3.3	16.1	3.2	16.6	3.7	16.2	3.3
1998	12.3	1.6	15.6	3.3	15.6	3.3	15.9	3.6	15.6	3.4
1999	11.6	-2.3	14.8	3.3	14.9	3.4	15.0	3.5	14.9	3.4
2000	9.7	-2.8	12.2	2.5	12.8	3.1	12.2	2.5	12.4	2.7
2001	11.1	-2.9	14.1	3.0	14.3	3.1	14.3	3.2	14.2	3.1
2002	11.7	-0.1	14.6	2.9	14.8	3.0	14.9	3.1	14.7	3.0
2003	10.7	1.6	13.8	3.1	14.2	3.5	13.9	3.2	13.9	3.2
2004	15.2	4.0	19.2	4.0	18.6	3.4	19.7	4.6	19.1	3.9
2005	14.0	-0.9	17.4	3.4	17.0	3.1	17.8	3.8	17.3	3.4
2006	10.8	-2.6	13.7	2.9	14.1	3.3	13.8	3.0	13.9	3.0
2007	14.0	-0.8	17.4	3.4	17.0	3.0	17.9	3.9	17.4	3.4
2008	11.3	-0.9	14.0	2.7	14.2	2.9	14.2	2.9	14.1	2.8
2009	14.3	-0.7	17.7	3.4	17.2	3.0	18.2	3.9	17.6	3.3
2010	11.7	-0.6	14.6	2.9	14.7	3.0	14.8	3.1	14.7	3.0
2011	11.1	0.4	14.4	3.2	14.7	3.6	14.5	3.3	14.5	3.4

with warm temperatures and high T_{ws} and T_a differences was 1990. In 1990, the mean T_a was the second highest (14.9°C), but the AMJ T_a was slightly above average 0.7°C. 2005, 2007 and 2009 were three years with next highest mean July 1st - August 15th T_a. The hindcasted mean T_{ws} for all water-bodies were also among the highest five during these years, but T_{ws} and T_a differences were close to average with a high one for Mosquito Lake in 2007 and a low one for Vortac Lake in 2009. Conversely, in 1992 and 1993, the mean July 1st - August 15th T_a were close to average and the hindcasted mean T_{ws} were just slightly above average in all four water-bodies; however, the temperature differences between T_{ws} and T_a were among the highest five for all water-bodies. The mean AMJ T_a was one of the smallest (-3.7°C) in 1992 and one of the highest (0.8 °C) in 1993.

In 2000, the smallest values were in almost every category. The mean air temperature (July 1st - August 15th) of 9.7°C was the lowest out of all years, the hindcasted mean surface water temperatures were also the lowest for all four water-bodies (12.2 – 12.8°C). The differences between T_{ws} and T_a were among the five highest for all water-bodies except Vortac Lake (2.5 – 2.7 (3.1)°C) and the mean AMJ air temperature in 2000 was -2.8°C, which was among the five minimum AMJ T_a. Although in 2008 the mean T_a and the mean AMJ T_a were both close to average, all the other categories had small values with hindcasted T_{ws} of 14 – 14.2°C and (T_{ws} - T_a) of 2.7-2.9°C. Similarly, in 2006, the hindcasted T_{ws} of 13.7 – 14.1°C were among the lowest for all water-bodies and (T_{ws} - T_a) of 2.9- 3.3°C were among the five lowest for Devil's and Mosquito Lake. 2003 and 1988 were two years with low mean T_a and mean hindcasted T_{ws}, but did not record many extremes among the (T_{ws} - T_a) ranges.

CHAPTER 4: DISCUSSION

Because of the dependency of water density on water temperature, during summer months, a lighter warmer water layer is atop of a heavier colder water layer. The mean T_{ws} and T_{wb} of the monitoring time period of June 22nd-August 28th 2011 ranged between 14.4 and 14.6°C and between 13.5 and 14.3°C respectively. The maximum daily mean T_{ws} and T_{wb} ranged between 18.2 and 19.5°C and between 17.6 and 19.3°C respectively. The minimum daily mean T_{ws} and T_{wb} ranged between 10.7 and 11.6°C and between 10.7 and 11.5°C respectively. For most of the time the warmer water was atop the colder layer and the ranges listed above showed such pattern as well; however, interestingly on July 4th, Devil's Lake developed a "thermal inversion". The daily mean bed water temperature was higher than the daily mean surface water temperature (Tables 3.1 and 3.2, Figures 3.5 and 3.7). This occurred after a rapid drop of air temperature by 10°C from about 16°C to 6°C in less than a week. On July 4th, Devil's Lake recorded both, its minimum daily mean T_{ws} and T_{wb}, with T_{ws} of 10.9°C and T_{wb} of 11.1°C. I believe this phenomenon occurred because the cooling of the surface water layer happened on much greater rate than was the rate of mixing caused by difference in water density.

In my study, I have confirmed the significant effect of air temperature on surface water temperature (Figure 3.5). I have observed a difference between surface water temperature and air temperature of +3 to 4°C during air temperature lows and cooling and a much smaller difference during air temperature rises and warm peaks. The differences between the overall mean T_{ws} and T_a ranged from 3.2 to 3.5°C and between the overall mean T_{wb} and T_a ranged from 2.4 to 3.2°C. Therefore, I can confirm findings of Kettle et al. (2004) and of Arp et al. (2010), that in high latitudes the lake water temperature is greater than air temperature during summers. I found a similar (T_{ws} - T_a) difference as Arp et al. (2010) in their study of Alaskan Arctic and Subarctic lakes. In late summer, Arp et al. (2010) observed differences ranging from 2.4 to 3.2°C in Arctic and from 1.7 to 5.4°C in Subarctic lakes. Latitude-wise, the water-bodies in my study (67°N) are located approximately in between of the lakes studied by Arp et al. (2010) (64°N and 71°N). However, I recorded much smaller (T_{ws} - T_a) difference than Kettle et al. (2004) who researched lakes in the same latitude (67°N) in Greenland. They found that the water temperature was typically 4-7 °C warmer than the air temperature. I assume that the difference between my results and their results is due to very different lake morphology as most of the Greenland lakes in their study were much deeper (3.5 -47 m). In contrast an earlier study by Livingstone et al. (1958) of lakes on the North Slope and in the foothills of Brooks Range, in July and August 1951, studied lakes (10 and 18 m in depth) had T_{ws} of 13.1 and 9.5°C which was 0.3 and 5.9°C, respectively, lower than the air temperature. Both lakes, in spite of their much greater depth than lakes in my study, were mixed with a temperature difference between T_{ws} and T_b of 0.4°C (on 10 m depth) and a temperature difference between T_{ws} and T_b of 0.7°C (on 18 m depth).

I have observed and calculated a time delay between air temperature peaks and water temperature peaks, and generally, the delay was between 1 and 3 days. Although the studied lakes are quite shallow, I have observed several periods of stratification (Figure 3.5). I have calculated the percentage of time water-bodies were stratified during summer 2011; lakes were considered stratified when bed and surface water temperature difference was equal or greater than 1°C. Devil's Lake was stratified over the longest time period – in total for over 1/3 of time. I believe it is due to its depth – over 3.5 m. I have also observed the greatest temperature difference of 4.2 °C between bed and surface in Devil's Lake, again because it is the deepest out of the four water-bodies. Vortac Lake and Lagoon showed a very similar statistic being both stratified for total of about 20% of time. The greatest temperature difference measured was a little over 3°C in both lakes. Vortac Lake and Lagoon are both about 2 m deep. Mosquito Lake is the shallowest with a depth of about 1.5 m and shortest total period of stratification, less than 10%, and smallest extreme difference in bed and surface water temperature – less than 2°C. Therefore, I confirm a clear dependence of stratification patterns on lake depth. From observed summer stratification patterns, I classify studied water-bodies as Cold polymictic lakes. If I studied stratification patterns over a course of an entire year, I could possibly find out about winter stratification and spring/fall mixing, and then lakes would be classified as Discontinual polymictic lakes. However, according to Kalff's (2001) description of Cold polymictic lakes, the shallower lakes (< ~ 20 m) finely stratify during warmer days and turnover at night and deeper lakes stratify for up to several days or weeks. Such description I cannot confirm, because our studied water-bodies are very shallow (< ~ 4 m) and all occasionally stratified for longer periods of time than a single day.

The stratification was especially present during increases in temperature. During periods of decreasing temperature, lakes experienced mixing. I believe that the mixing was due to two processes: 1) sinking of the top water layer of which density increased because of cooling induced by colder atmosphere; and 2) turbulent water movements caused by storm events and associated wind which accompanied the colder weather (Figures 3.6, 3.7 and 3.8). It is difficult to assess which of the two processes had a major role as they occured simultaneously. The lake stratification periods were related to low wind speeds and the mixing periods to high wind speeds as the comparison of wind speeds and the (T_{ws} - T_{wb}) indicating stratification showed.

For data modeling and hindcasting, Model 2, the model calculating with the Kotzebue airport T_a and TCRS, was used (Table 3.7, Figure 3.15) . I have calculated model parameters **a**, **b**, **c**, and **α** for each water-body and compared my results to the results of Kettle et al. (2004) and Arp et al. (2010), who used the same modeling approach (Table 4.1).

Table 4.1 Comparisons of model parameters calculated for water-bodies in Kotzebue with parameters calculated by Arp et al. (2010) for Subarctic and Arctic Alaskan lakes and with parameters calculated by Kettle et al. (2004) for lakes in Greenland.

Study	Latitude	α range	a range	b range	c range
Arp et al.	64° N	‹0.04, 0.07›	‹-10.77, 0.80›	‹1.13, 1.64›	‹0.002, 0.005›
Bendlova	67° N	‹0.19, 0.30›	‹-4.88, -3.55›	‹1.00, 1.32›	‹0.009, 0.014›
Kettle et al.	67° N	‹0.09, 0.37›	‹-0.26, 5.39›	‹0.53, 1.03›	‹0.003, 0.014›
Arp et al.	71° N	‹0.21, 0.49›	‹2.98, 4.16›	‹1.09, 1.47›	‹-0.007, -0.005›

All specific parameters had similar magnitudes. Although the lakes in each of the three studies had different morphologies, there seems to be a pattern in the model coefficients in relation to geographical location. The ranges of model parameters **α** and **a** increased with latitude. **b** range in my study resembled the most Arp et al.'s range of lakes in higher latitudes and **c** range in my study resembled the most Kettle et al.'s range of lakes in same latitudes. Latitude is, therefore, an important predictor of model parameters estimating lake thermal regimes; however, the model parameters cannot be extrapolated on non-monitored lakes just based on their latitude, because for example lake morphology (surface area, depth) is also a major indicator of lake thermal regimes. Obtaining datasets from a sufficient number of monitored lakes with varying morphology across latitudal gradient could probably make predicting model parameters possible.

Comparing the observed and modeled surface water temperatures in summer 2011, I have noticed an interesting pattern such that the model overestimated the surface water temperatures from July 1st until about July 18th-20th. Then modeled values were largely underestimating the surface water temperatures for the rest of July and then were about right for the ten last days of the studied period (Figure 3.15, Table 3.8). It is probably due to the fact that water has the ability to store heat. Model parameters **a**, **b** and **c** are constant for the studied period of time and were calculated from even longer monitoring time period (June 22nd – August 28th). The estimation of the model parameters therefore does not account for the fact that water has stored more heat by the end of July – beginning of August, than it had stored in the beginning of July.

I have hindcasted surface water temperatures back until 1985 and found out that in all four water-bodies, surface water temperatures differ substantially between years (Figure 3.17). However, any obvious past temperature trends, such as gradual increase of mean annual temperatures (time period July 1st – August 15th), are not revealed. However, these estimates may be inaccurate and could be both, higher or lower, than real values for following reason: Model parameters **a**, **b** and **c** for hindcasted period of time, July 1st – August 15th, were estimated in 2011 with two additional weeks of data in late August and one additional week in late June when temperatures were monitored. I estimated the predictor parameters with use of a slightly longer period of time, because I needed larger dataset of observed values to base our model on. Nevertheless, the predictor parameters developed from larger dataset may create bias on modeling the shorter period of time, because the June temperatures were higher due to 24 hours of daylight, but water did not have as much of heat stored yet. On the other hand, in second part of August there was more heat stored in the water, but air temperatures were lower on average than during previous months. Therefore, because our model accounts only for air temperature and solar radiation and not for heat storage mechanisms, it would be beneficial for our study to have data covering even longer period of time in summer 2011 and break these down on shorter periods than our modeling period was. Then multiple model parameters **a**, **b** and **c** should be estimated for each lake for short periods of time in order to estimate surface water temperatures with a greater accuracy.

As for the differences among studied water-bodies, Mosquito Lake showed the greatest range of extremes. Hindcasting annual mean, maximum and minimum surface water temperatures for July 1st- August 15th, Mosquito Lake recorded the highest ranges, and the max and min temperatures of Mosquito Lake were the highest and the lowest respectively (Figures 3.17, 3.18 and 3.19). On the other hand, these hindcasted values gave the smallest range for Vortac Lake, which of maximum T_{ws} were the lowest and minimum T_{ws} were the highest. In search for an explanation, I first compared lake mean depths because depth certainly plays an important role in thermal regimes as it affects stratification and mixing and the heat storage capacity. Mosquito Lake's was 1.6 m (the shallowest) and Vortac Lake's was 2.28 m. Because Lagoon's depth was 2 m and Devil's Lake's depth was 3.7 m, I could not explain the distribution of ranges among the studied water-bodies solely by differences in depth, because then the smallest range would be attributed to Devil's Lake which is the deepest (greatest heat storage and least mixing). On the other hand, Mosquito Lake's greatest range of monitored and hindcasted T_{ws} could be explained by its depth, because it is the shallowest out of the studied water-bodies.

Why was Vortac Lake's range of extremes the narrowest? In search for an explanatory variable I thought of water level changes (Figures 2.8 and 2.9). Vortac Lake experienced significant decrease of water level due to water extraction for municipal drinking water system. The water was moved and therefore its temperature could have been moderated. Devil's Lake and Lagoon also experienced water level changes but not as much as Vortac Lake. Mosquito Lake has not substantially changed its water level. This is the main difference I discovered which could explain the width of temperature ranges of studied water-bodies. Other variables which could affect the thermal regime ranges are lake area, watershed area, local wind patterns, prevailing wind direction, and proximity to the coast. The movement of water caused by water extraction in the managed water supply lakes could foster moderation of extremes in the managed lakes.

The distribution of hindcasted minimum and maximum daily mean T_{ws} values for each year's July 1st-August 15th period was determined (Figure 3.20). The minimum daily mean T_{ws} values fell either into first two weeks of July or last two weeks in August and the maximum values largely happened in July. For understanding of this trend, I created the Table 3.9

comparing various criteria of each year. It appears that the years with maximum daily mean T_{ws} in early July were also years with warmer mean April-May-June T_a (1988, 1989, 1990, 1991, 2003, 2004, and 2011). Colder mean April-May-June T_a generally fostered later occurrence of the maximum daily mean T_{ws} (1985, 1986, 1994, 2000, 2001, and 2005). The years not listed above did not show the same rule and either had colder AMJ T_a and early occurrence of max T_{ws} or vice versa. The distribution of minimum daily mean T_{ws} did not show a similar relationship to the mean April-May-June T_a.

Overall, the low number of predictor variables in this model has its positives as well as negatives. My predictions of water temperatures may be inaccurate just due to the low number of predictor variables, because air temperature and solar radiation are not the only phenomena which affect surface water temperature. For example, wind and latent heat also play major roles as well as lake morphology. However, the biggest advantage of this model is the ability to estimate surface water temperatures in areas where very limited predictor data are available.

Long-term hindcasted surface water temperatures did not reveal any obvious trend in relation to the climate change. I noticed significant differences among years in average, maximum and minimum values for July 1st – August 15th. Probably study of lake thermal regimes with use of yearlong datasets could reveal some trends in relation to climate change such as earlier ice-out and later ice-on events. If I were to model year-round thermal regimes of these lakes, I would rather determine modeling parameters α, a, b, and c for each water-body for shorter time steps than the entire ice-out time period, in order to make more accurate estimates.

If the water supply lakes changed their thermal regimes, it would impose consequences on the environment as well as the local community. The advantages of warmer water in the supply lakes would be that less energy is spent on heating the piped water and on bubbling by intake point. That would save the WTP money. The disadvantage would be possibly altered water quality by changed water chemistry as reaction rates tend to increase with rising temperatures. Most importantly, the warmer water would facilitate growth of pathogenic microbes as well as algal blooms which release toxins into the water and diminish its taste. The water treatment plant operators noticed that algal blooms raise pH as CO_2 is largely removed from water and also soften water by extraction of Magnesium for use in chlorophyll structure.

Powdered activated carbon (PAC) has been used in the WTP since August 2005 to cope with unpleasant taste and odor associated with algal blooms (Matthew Lazarus 2011, personal communication). Our hindcasted records show that summer 2005 T_{ws} were above average; however, T_{ws} in summer 2004 were even higher. After 2005, 2007 and 2009 were also warmer than average (Figure 3.17). It would be particularly useful to have detailed information on algal bloom events in the studied lakes. Knowing exactly when the algal blooms developed in the lakes and monitoring lake and climatic conditions during such events would be useful for future predictions of their emergence, duration and severity. Optimum for cyanobacterial growth is 25°C, limiting is 15°C (Robarts & Zohary 1987). Correlating the algal bloom occurrence to surface water temperatures would also be very beneficial information for other Arctic communities relying on lakes for water supply.

Other problems which could arise are associated with warming air temperatures and the fact that the water supply lakes are thermokarst lakes. Because thermokarst lakes are characterized by shoreline erosion, their basins are expanding. And consequently release of soluble materials from degrading permafrost could alter water quality (Kokelj et al. 2005). Also, altered water balance, shrinking and catastrophic drainages of thermokarst lakes have been described (Yoshikawa & Hinzman 2003). Changes in Arctic lakes and differences in water quantity and availability have been observed in other studies in relation with warming Arctic, so climate change could possibly threaten the sustainability of lakes as a reliable water source (Plug et al. 2008; Jones et al. 2011).

The drinking water source lakes represent the crucial part of the municipal water system in Kotzebue. From our findings, it seems that in long-term perspective, the source lakes are quite vulnerable parts of the system, because of their thermokarst character. However, it is uncertain how long the lakes stay in their current or close to current condition before any significant changes occur. Currently, in order to keep raw water in the best condition it can be, it is necessary to prevent its contamination. I have discovered four-wheeler trails right on the Devil's Lake shore and seen many related oil spills which were located in areas with run-off into the lake. Another problem with possible contamination of raw water by petroleum products could occur in winter, because there is a snow-machine trail right across frozen Devil's Lake. Climate change in the area could foster possible accident as if time of ice-out occurred earlier than the local inhabitants have been used to for years, thinning ice could break under a snow-machine which would not only cause water pollution but also would threaten human life. Therefore, I suggest building a fence around the source lakes as to prevent contamination of the raw water for the drinking water system.

The drinking water system has been well and responsibly managed. Most of the technical issues are not related to the Arctic climate and are common in other plants. However, the possible Arctic specific issue is that the distribution system is susceptible to problems related to changes in permafrost and occasional movements of the ground. I predict that a suggested warming trend of the area could induce more frequent problems with broken pipelines and associated water contamination.

There is still a need to better understand the impacts of climate change on freshwater ecosystems as they relate to change in human economies and health (harmful algal blooms). Understanding the climate change is essential for adaptation to it. Baseline data can be utilized in climate change studies, habitat evaluations, and land and resource management.

CHAPTER 5: CONCLUSIONS

Climate in Kotzebue (66°54'N 162°35'W) has been changing as shown by increases in the mean annual air temperature by 1.4°C in time period 1985-2011 and increases in summer mean temperature by 0.6°C over the same time. However, as p-values indicate, these trends are statistically insignificant. Because of the direct response of lake surface water temperature to air temperature and solar radiation in summer season, changes in thermal regimes of studied water-bodies are expected. Lakes used for municipal water supply in Kotzebue, Devil's and Vortac Lakes, responded to changes in air temperature and solar radiation in a very similar manner as an alike unmanaged water-body, Mosquito Lake. During the monitoring time period, June 22nd-August 28th 2011, the mean T_{ws} ranged from 14.4 to 14.6°C, the max daily average T_{ws} was 19.5°C and the min daily average was 10.7°C. Stratification and mixing were observed in all water-bodies for multiple times and various durations. Wind proved to be one of the factors. The max difference (T_{ws} - T_{wb}) recorded was 4.2°C in 3.6 m depth. T_{ws} was greater than T_a for most of the time and the mean difference was 3.2 – 3.5°C. This result is similar to the difference of 2.4 - 3.2°C observed by Arp et al. (2010) in Arctic Lakes.

Interannual variation in lake thermal regimes was estimated based on models developed from T_a, TCSR, and monitored T_{ws} in each water-body (**α**=‹0.19, 0.30›; **a**=‹-4.88, -3.55›; **b**=‹1.00, 1.32›; **c**= ‹0.009, 0.014›). Although I have noticed significant fluctuation among years of the mean (12.2 – 19.7°C), minimum (6.6 – 16.7°C), and maximum (15.6 – 25.2°C), T_{ws} for time period July 1st – August 15th, I have not observed any emerging patterns showing increasing trends in surface water temperatures with time (1985 – 2011) which would confirm effects of climate change. A pattern I observed was that the minimum daily mean T_{ws} values fell either into first two weeks of July or last two weeks in August and the maximum values largely happened in July. The max T_{ws} in early July can be explained by warmer mean April-May-June T_a. Possible warming trend of surface water temperatures would likely alter quality and quantity of lake water used for drinking purposes for the City of Kotzebue, especially because the source lakes are of thermokarst origin. However, I am unable to predict from our baseline data, if such problem is to occur and if so, in what time frame. The most current problem regarding the municipal water system is possible contamination of source lakes from activities taking place in the area. I recommend that future scenarios are discussed and planned for the City of Kotzebue in regard to use of alternative source of water such as brackish ground water or seawater.

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